Implementation of Design Failure Modes and Effects Analysis for Hybrid Vehicle Systems

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ACADEMIC ABSTRACT

An increase emphasis has been placed on the automotive industry to develop advanced technology vehicles which meet increasing strict government regulations and standards for emissions and fuel economy while maintaining the safety, performance, and consumer appeal of the vehicle. In response to these requirements, hybrid and electric vehicle technologies have become more complex as the necessity for vehicles with an overall better environmental impact. Modern engineers must understand the current methods used to analyze and evaluate risk with the new hybrid technologies to ensure the continued customer satisfaction and safety while meeting new government and agency standards.

The primary goal of this work is to maintain consistent definitions, standards, and protocols for risk analysis using design failure modes and effects analysis. Throughout the entire automotive sector there exist standards for risk analysis and methods for analysis, however these models can be difficult to relate to the atmosphere under which educational competitions occur. The motor system case study within this work aims to allow the process for DFMEA to be simple and easily implemented and understood when it is appropriate to start. After defining the model, an electric motor system for hybrid vehicle is analyzed for mechanical and inverter system risks. The end result being a 32% reduction in motor system risk due to recommended actions for mitigating top motor systems risks for future motor system design and implementation, all to meet customer requirements. This work aims to provide an additional tool that when implemented will accelerate the next generation of automotive engineers.

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GENERAL PUBLIC ABSTRACT

An increased emphasis has been placed on the automotive industry to develop advanced technology vehicles to meet rising strict government regulations and standards for emissions and fuel economy while maintaining the safety, performance, and consumer appeal of the vehicle. As a result of the new legislation, complex systems for hybrid and electric vehicle technologies have been developed to improve fuel economy and reduce criteria tail pipe emissions. Modern engineers must understand the current methods used to analyze and evaluate risk with new hybrid technologies to ensure continued customer satisfaction and safety while meeting new government and agency standards.

Throughout the entire automotive sector there exist standards and methods for risk analysis, however these models can be difficult to apply to student design project. The student designed motor system case study within this work aims for DFMEA to be simple and easily implemented by students, increasing the educational experience. After defining the model, a motor system for a hybrid vehicle is analyzed for mechanical and inverter system risks. The end results are the recommended actions for mitigating top motor systems risks for future motor system design and implementation, all to meet customer requirements and reduce system risks. This work provides an additional tool that when implemented will advance the educational experience for the next generation of automotive engineers.

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List of Terms & Abbreviations

ADAS	Advanced Driver Awareness System
AFM	Active Fuel Management
AVTC	Advanced Vehicle Technology Competition
CAD	Computer Aided Design
CAE	Computer Aided Engineering
CAFÉ	Corporate Average Fuel Economy
CAN	Controller Area Network
CD	Charge Depleting
CFD	Computational Fluid Dynamics
CMRR	Consumer Market Research Report
CS	Charge Sustaining
D	Detection
DFMEA	Design Failure Modes and Effects Analysis
E&EC	Emissions & Energy Consumption
ESS	Energy Storage System
EV	Electric Vehicle
FEA	Finite Element Analysis
FMEA	Failure Modes Effects Analysis
FTA	Fault Tree Analysis
FTPs	Forward Thinking Patriots
GM	General Motors
GVDP	Global Vehicle Development Process
HEVT	Hybrid Electric Vehicle Team
HIL	Hardware In-The-Loop
HV	High Voltage
HVSC	Hybrid Vehicle Supervisory Controller
IQ-FEA	Intelligent Failure Modes Effects Analysis
IVM	Initial Vehicle Movement
LV	Low Voltage
MIL	Model In-The-Loop
NYSR	Non-Year Specific Rules
O	Occurrence
OEMs	Original Equipment Manufacturer
P3	Post Transmission Motor Position
PDO	Process Data Object
PEU	Petroleum Energy Use
PFMEA	Process Failure Modes Effects Analysis
RPN	Risk Priority Number
S	Severity

SAE	Society of Automotive Engineers
SCERT	Synergistic Contingency Evaluation and Review Technique
SFMEA	System Failure Mode Effects Analysis
SIL	Software In-The-Loop
SO	Criticality Number
SOC	State-of-Charge
UF	Utility Factor
US DOE	United States Department of Energy
VDP	Vehicle Development Process
VTS	Vehicle Technical Specifications
WTW	Well-to-Wheel

1 Introduction

1.1 FMEA and Importance in Automotive Industry and Advanced Vehicle Technologies

The automotive industry has long used failure modes effects analysis (FMEA) as means to improve customer satisfaction and reduce nonconformance (Stamatis 2003). For over 30 years FMEA has become more integral into American automotive companies to the point of the inclusion of FMEA into the companies quality standards. This rise in focus on risk management and mitigation through FMEA is so integral in the development process that Six Sigma, Production Part Approval Process (PPAP), Tooling and Equipment (TE 9000), ISO 9000, QS-9000, and ISO/TS16949 have all required FMEA as one of the suggested ways a company can improve. There is an increasing need for automotive companies to continually refine their execution methods of FMEA, taking into account the amount of time and money that is spent on recalls and part malfunctions on a system as complex as an automobile.

In recent years, an increased focus on systems safety and FMEA have been placed to not just solve problems once they happen but to reduce the likelihood of the risk In response to major recalls from various original equipment manufacturers (OEMs), thresholds for risks that need to be evaluated for some components and systems decrease the acceptable threshold. Advancement of vehicle technologies are required to meet increasing Corporate Average Fuel Economy (CAFE) requirements for vehicles with less emissions and higher fuel economy. Design FMEA (DFMEA) provides an engineering method for the new technologies and systems being implemented into the vehicles to track the risk involvement for each design and application. The risk management strategies must also evolve and be adapted to successfully quantify the risks involved as technologies advance.

1.2 Introduction to Types of FMEA

1.2.1 Systems FMEA

Prior to any design decisions being made, a SFMEA is conducted in a manner to include the initial concept, design iterations and developments, and concluding with test and evaluation(Stamatis 2003). The end goal of SFMEA is to define and demonstrate a balance among operational and economic factors for any given design. This is accomplished through setting the system requirements solely on the wants, needs, and desires of the customer. The end result of a well-developed system FMEA is a design with initial physical configuration and functional specifications derived from the established customer requirements(Stamatis 2003). The generated causes for systems failure modes are then implemented as the failure modes themselves for a specific system or subsystem DFMEA. Figure 1-1 shows the transitions and relationships throughout the most critical stages of FMEA.

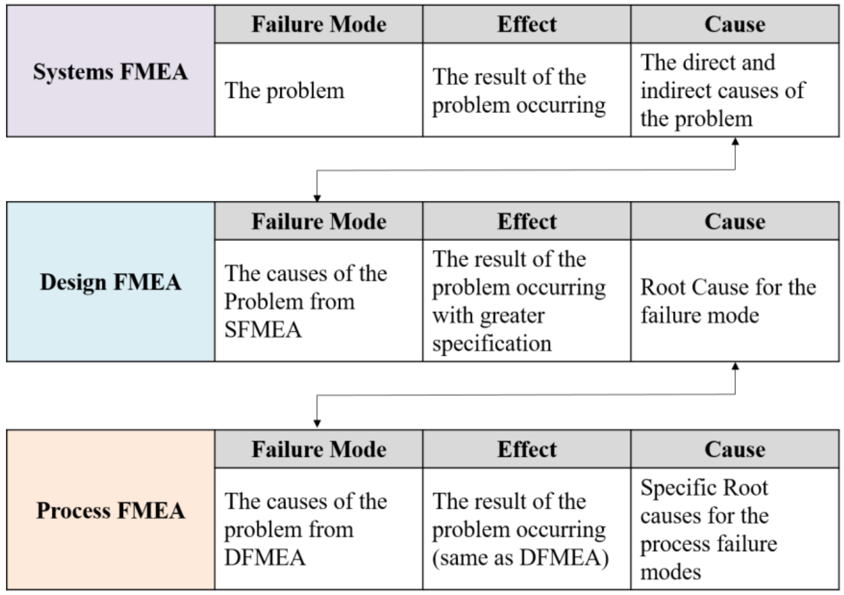

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Figure 1-1: FMEA Transition Process adapted from Stamatis (2003)

1.2.2 Design FMEA

Design FMEA is carried out following a successful SFMEA with primary focus of minimizing failure effects on the system, regardless of where in the development process the product may currently be. Similar to the SFMEA, DFMEA is critical in defining and describing viable solutions in response to potential failure modes of functional requirements prescribed by the customer. The operational needs of a design can be distilled down to a description of system performance parameters. DFMEA acts on the assumption that the system has been optimized and cannot be improved upon. This optimized system assumption is made to prevent the FMEA team from going back and forth between SFMEA and DFMEA.

Two primary approaches are taken when attempting a DFMEA: design-to-customer or design-to-cost requirements (Stamatis 2003).The first approach emphasizes the desire to provide for the customer requirements, while holding to safety concerns, company requirements, and government regulations. Secondly, the design-to-cost method determines early on in the design process a certain cost limit that is not be exceeded regardless of customer desires and requirements. In DFMEA, like all processes of FMEA, a team is required to successfully develop and maintain a live DFMEA. A recommended team will typically include:

1) System Engineer
2) Reliability Engineer
3) Test Engineer
4) Material Engineer
5) Process Engineer
6) Market Representative
7) Design Engineer

These roles are derived from Stamatis (2003) and the suggested team members for an effective DFMEA.

Although this work will focus primarily on SFMEA and DFMEA, there are two other FMEA steps necessary to see a design through to completion. Process FMEA (PFMEA) and Service FMEA. PFMEA is to happen before the first production run of a product occurs. Considerations from labor, machine, material properties, measurement, and environment conditions are all taken into account when performing a PFMEA. These six conditions are geared to achieving an end product that exceeds safety, reliability, and quality attributes of the design. The aim of PFMEA is to reduce the process failure effects on production parts. A successful PFMEA will define, develop, and optimize engineered solutions for responses to the quality, reliability, maintainability, cost and productivity which were taken from the DFMEA and end customer (Stamatis 2003). Finally, service FMEA evaluates various systems and components during the early phases of concept generation and design iteration in order to increase the serviceability of the end product (Stamatis 2003).

1.3 Introduction to Parallel Plug-In Hybrid Electric Vehicles

While many distinct types of FMEA exist, the thesis will focus on the application of DFMEA. On a complex system such as a hybrid vehicle understanding component interaction and failure modes from a systems level allows for a more refined and accurate DFMEA. The powertrain that is being analyzed is a post-transmission (Position 3 or P3), plug-in hybrid electric vehicle as seen in Figure 1-2.

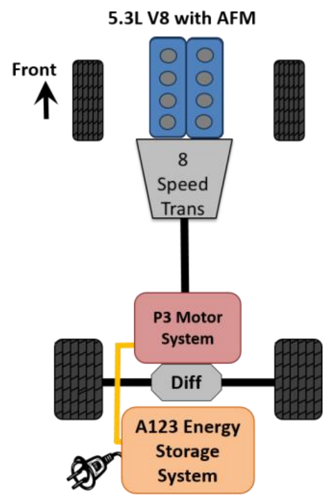

Figure 1-2: Diagram of P3 Parallel HEVT Camaro

In the front of the vehicle a 5.3L V8 internal combustion engine is coupled to an 8-Speed automatic transmission with active fuel management (AFM). AFM allows for the deactivation of four cylinders when specified driving conditions are met, increasing the efficiency of the vehicle. Following the drivetrain a custom P3 electric motor provides torque through the drive shaft to the rear differential. Power for the motor is supplied by a 12.6 kWh battery pack. This particular powertrain configuration allows for three distinct modes of operation.

In charge depleting (CD), the energy from the battery pack or energy storage system (ESS) is provided to the P3 motor which then drives the vehicle in pure electric vehicle (EV) mode. Charge depleting is the primary mode of operation given sufficient SOC and an accelerator pedal position within preset limits. Once either of the previous criteria are no longer true, the vehicle will then operate in charge sustaining (CS). The custom P3 motor is used to add or reduce the load that the engine sees to maintain a certain efficiency for the engine. Engine loading is done primarily to keep the engine in sufficient torque ranges to maintain AFM. Engine assist supplies additional torque when needed from an increased torque demand. The P3 motor will supplement the torque requested to keep the engine operating in a RPM range for increased vehicle efficiency.

The importance of the P3 motor system cannot be overstated as the functionality of the component is required for all modes of operation. Early on in any design process requires understanding of the desires of the customer, being both the end user, but also the design responsible engineers, and various subteams of the vehicle design (Standard 2002).

1.4 EcoCAR 3: Advanced Technology Vehicle Competitions

1.4.1 Introduction

The desire to produce a refined DFMEA of a motor system and develop a repeatable, implementable FMEA process is due largely to the authors' involvement with Virginia Tech's Hybrid Electric Vehicle Team (HEVT). HEVT is competing in the most recent Advanced Technology Vehicle Competitions (AVTC) series, EcoCAR 3, which is organized by Argonne National Laboratory (ANL) with headline sponsors of General Motors (GM) and the United States Department of Energy (US DOE). The EcoCAR 3 competition tasks 16 universities between the United States and Canada to re-engineer a 2016 Chevrolet Camaro into a fully functional hybrid electric vehicle. The main goals of this competition are to reduce the wheel-to-well (WTW) petroleum energy use (PEU), WTW greenhouse gas emissions and criteria emissions, while maintaining the safety, performance and consumer acceptability of the vehicle (ANL 2015). In EcoCAR 3, unlike past competitions, there is an increased focus on the component cost energy costs, and the overall innovation of the teams' designs. Students gain invaluable experience working on and with hybrid technologies which prepare them to become immediate contributors in the future generation of automotive engineers. Guided by the vehicle development process (VDP), students follow a condensed version of GM's vehicle development steps in order to gain important insight and experience. A comprehensive FMEA for all systems and significant component subsystems is vital for the students to develop a vehicle within the confines of the VDP. FMEA provides important customer requirements, vehicle specifications, and guides the entire design of the vehicle and has not been a thoroughly integrated part of the competition until recently.

1.4.2 HEVT Team Structure

Being comprised of nearly 75 active and contributing members, HEVT is divided into six technical subteams along with project management and communications subteams. The six technical subteams are: Mechanical, Electrical, Controls, Systems Modeling & Simulation, Systems Safety, and Advanced Driver Awareness System (ADAS). The mechanical subteam is responsible for the integration of hybrid and conventional components in the vehicle platform both in CAD and on the vehicle. The electrical subteam determines required wire sizing and fusing requirements for both the low voltage (LV) and high voltage (HV) systems of the vehicle and are the primary subteam responsible for the assembly of the energy storage system. The Controls and Systems Modeling & Simulation subteams work closely together to develop refined plant models and vehicle control code to progress through the vehicle controller development process. The Systems Safety subteam is result of competition increased focus on insuring vehicle functionality does not jeopardize the safety of the customer. This work will suggest proper methods for implementing a successful System Safety subteam that spans all technical and nontechnical subteams. Concluding the technical subteams is the newly integrated ADAS subteam which works with state of the art technology to develop systems to allow the vehicle to detect and process crucial pieces of information from stop signs, sudden vehicle decelerations, and as a result command various actions from the vehicle to increase the fuel economy and decrease the energy consumption of the vehicle. The project management team is responsible for the project timing, budgeting, human resource acquisition and maintenance, as well as the overall efforts for knowledge transfer from one year to the next. Finally the communications team is in charge of all the teams' form of social media, print media, and aids in increasing awareness of EcoCAR 3 on Virginia Tech's Campus, the surrounding area, and promoting sustainable energy to the next generation of car buyers and the work force. The automotive industry is moving more and more to hybridized vehicle powertrains, requiring new skill sets that EcoCAR 3 provides to these students.

1.4.3 VDP

Prescribed by EcoCAR 3, HEVT's project timing follows GM's global vehicle development process (GVDP) on a condensed timeline that enables the decoupled development of subsystems and international work sharing (ANL 2016).

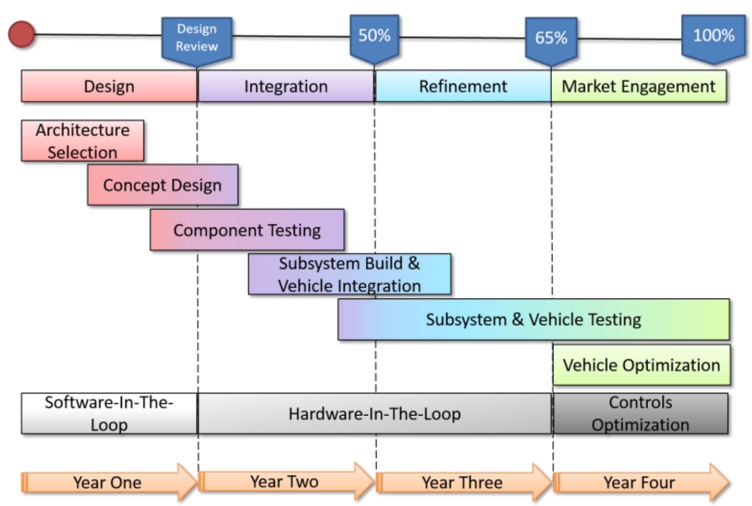

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Figure 1-3: Vehicle Design Process ANL (2016)

At the onset of Year 1 HEVT was informed that the vehicle platform for EcoCAR 3 would a 2016 Chevrolet Camaro. Prior to any powertrain being selected for the remainder of competition and in depth Consumer Market Research Report (CMRR) was conducted to determine the target market for the Camaro. Upon determining the target market to be the

Forward Thinking Patriots (FTPs) a feasibility study was conducted to propose five powertrain configurations (HEVT 2014). These five options utilize different energy flows, including series, series-parallel, and parallel-through-the-road. A literature review was conducted on battery sizing and CAFE requirements to provide insight on team specific environmental goals. Some constraints of the feasibility were driven by control strategy complexity, fuel type and environmental impact while others were to remain in compliance with the EcoCAR 3 rules. From the feasibility study additional technical team goals were created to guide the design process by adding an internal customer and can be seen in Table 1-1.

Table 1-1: Team Goals

HEVT Technical Team Goals
Meet all minimum competition requirements
Avoid designs that incur known penalties
Meet 2020 CAFE standards for Camaro Class Vehicle
Maintain Camaro stock seating for four persons
Maintain 100% torque on rear axle (Rear wheel drive)
Match performance of V8 model, while improving fuel economy to surpass that of V6 model

These team goals provided a scope for the vehicle design that designs are held to throughout the remainder of the competition. Later in Year 1 a Powertrain Selection study was conducted to put forth four viable powertrains that would meet both HEVT team goals and competition requirements. Table 1-2 below shows the competition target required, the target, and HEVT team target vehicle technical specifications (VTS).

Table 1-2: VTS

Specification	**Competition**		**HEVT Target**
	Req.	**Target**	
Acceleration, IVM-60 mph, sec	7.9	5.9	5.0
Acceleration, 50-70 mph (Passing), sec	9.9	7.3	5.0
Braking, 60-0 mph, ft	135	128	128
Acceleration Events Torque Split (Front/Rear)	49% F 51% R	0% F 100% R	0% F 100% R
Lateral Acceleration, 300 ft. Skid Pad, G	0.80	0.85	0.85
Double Lane Change	52	55	58
Highway Gradeability, @ 20 min	6% @ 60 mph	6% @ 60 mph	6% @ 60 mph
Cargo Capacity, ft^3	2.4	--	>2.4
Passenger Capacity	2	4	4
Curb Mass, lb (kg)	TBD	--	≤ Comp. Req
Starting Time, sec	15	2	2
Total Vehicle Range*, mi (km)	150 (226)	--	187 (300)
CD Mode Range*, mi (km) Pure EV	N/A	--	22.5 (36.2)
CD Mode Total Energy Consumption*, AC Wh/km (mpgge)	N/A	--	280 (74.8)
CS Mode Fuel Consumption*, Wh/km (mpgge)	N/A	--	840 (24.9)
UF-Weighted Fuel Energy Consumption*, Wh/km (mpgge)	N/A	--	480 (43.6)
UF-Weighted AC Electric Energy Consumption*, AC Wh/km	N/A	--	120
UF-Weighed Total Energy Consumption*, Wh/km (mpgge)	840 (25)	700 (30)	600 (35)
UF-Weighted WTW Petroleum Energy Use*, Wh PE/km	750	420	150
UF-Weighted WTW Greenhouse Gas Emissions*, g GHG/km	250	225	175

*Evaluated by using the EcoCAR 3 combined "4-cycle" weighting method. NM – Not Modeled, IVM – Initial Vehicle Movement, UF – Utility Factor, WTW – Well to Wheel, WTP – Well to Pump, mpgge – Miles Per Gallon Gasoline Equivalent, P1- Position 1, P3 - Position 3

These VTS with DFMEA represent the customer, as well as regulatory agencies, and requirements for the design. As required by competition the initial vehicle movement (IVM) to 60 mph time must be equal to or less than 7.9 seconds. Along with increased emphasis on the performance of the vehicle, EcoCAR 3 continues to strive to improve upon the emissions and energy consumption. Several design modifications to passenger seating and storage space were balanced with the competition enforced penalty for failing to meet passenger seating capacity. There are 22 individual specifications that were designed to guide the vehicle powertrain to meet customer requirements and have been limited by a maximum and a competition suggested target specification to remain competitiveIn Year 1 the customer and target market were defined, a feasibility study was conducted to determine powertrain configurations that would meet both customer requirements, but also team goals. The end user was identified as the Forward Thinking Patriot through research completed in the CMRR. The FTPs desires in the vehicle will be articulated down to the design level for each component system. HEVT selected four powertrains to simulate in vehicle powertrain software Autonomie, perform space claim studies in CAD, and determine the powertrain configurations ability to meet competition required and team target VTS.

The four powertrain proposed were placed into a selection matrix to determine objectively which powertrain best met all requirements. However, a heavy emphasis was placed upon more than simply meeting competition minimum requirements but as a whole of the team desire to maintain the heritage of the Camaro. Prior team experience, facilities, budget, and component complexity were all taken into account when choosing a V8, P3-parallel plug-in hybrid electric vehicle as the vehicle that best met the VTS and customer requirements. The hallmark piece of each proposed powertrain is a student/industry collaboration on a custom P3 motor and is the critical path for all modes of operation. The P3 motor for timing, complexity, and integration is the subsystem with the most risk and this work aims to prescribe a method to reduce risk with preemptive actions for known and potential risks.

1.4.3.1 <u>Year 2</u>

Concluding Year 1, a powertrain and VTS that the built vehicle is compared against for the remainder of the competition. Year 2 of the VDP is the component subsystem bench testing and component integration into the donated vehicle. The emphasis in the Fall of Year was to finalize any remaining designs, modify component mounts, and refine the controller model-in-the-loop (MIL), controller software-in-the-loop (SIL), the genesis of hardware-in-the-loop testing. Bench testing of the batteries that would form the ESS began with LV communication and verifying the ability to open and close the battery contactors. The Vehicle Design Report was submitted in December 2015 which marked the end of the design phase of the VDP. DFMEA for the P3 motor system also began as the FMEA team was created and the design analyzed. The team subjectively determined that the highest risk component system as a whole is the P3 motor system. Upon receiving the vehicle in late December of 2015 a baseline evaluation was done for controls and reading CAN information, mass and ride height studies for vital information of how the components added to the vehicle will affect handling. The competition goal for the conclusion of Year 2 of 50% ready mule vehicle with all components successfully integrated but not required to work with full functionality. At the conclusion of Year 2 the DFMEA should be reevaluated for all component systems based upon the system specific recommended actions.

1.4.3.2 Year 3

The third year of competition has the goal of reaching a 65% vehicle in which all major operational modes are working but may not be completely refined for performance or fuel economy. Redesign of an overdesigns or unnecessary complexities from Year 2 will be reevaluated and possibly redesigned. Team goals and competition requirements will allow the team to understand areas in which the Year 2 vehicle failed to meet expectations. A thorough light-weighting strategy will be carried out to ensure no unnecessary mass has been added to vehicle. HIL testing will continue to refine the models for each component and vehicle simultaneously while performing in-vehicle testing to gain high fidelity information. At this point in the competition, FMEA should be solely focused on a PFMEA due to designs being past design freeze and into vehicle integration.

1.4.3.3 Year 4

The fourth and final year of EcoCAR 3 will focus heavily on producing a showroom quality, 99% ready, vehicle at the final competition. The control code MIL, SIL, and HIL are to be all continually refined to better reflect actual vehicle operation. The CAD of the Camaro will continuously be refined to accurately represent the vehicle that has been built with all components properly packaged, routed, and mounted. Unlike previous years, Year 4 will have an increased emphasis on market engagement which will allow teams to validate if their designs and vehicle have met the competition targets, team goals, and consumer requirements that were prescribed in Year 1 and Year 2 of the competition. All selected component systems DFMEA and PFMEA should be concluded by the conclusion of the fourth and final year. There are always improvements that can be made, however a consensus must be reached to move forward and make progress.

1.4.4 Summary

EcoCAR 3 accurately represents the GVDP set forth by GM throughout the four years of competition. The market research, feasibility study, component bench testing, subsystem testing and integration, and vehicle optimization combine to cover all aspects of a design giving an unparalleled experience for students. This work becomes valuable during the first few years of the competition for any design team to accurately and objectively understand the risks involved with component selection and the component relationship back to consumer and team requirements. A model and thorough example of DFMEA is provided for a high risk component, the P3 motor system. The implementation of this method in varying competitions will allow teams to identify the highest risk designs well ahead of time, allowing for planned corrective actions, and increased safety and success. Similarly, the methods that will be described are easily applied to a SFMEA or PFMEA and should be done to follow best practices for automotive industries.

1.5 Application in EcoCAR 3

While the competition has already started, many systems and component designs are continually undergoing review and revision to better meet the team requirements. This thesis will provide a layout of the motor DFMEA and the major risks associated with undertaking such a design. Future members will be able to take this example and the procedure provided to develop and analyze all major subsystems and components of the vehicle.

Purpose, Goals, Objectives.

1) Develop a method of DFMEA that is repeatable and actionable for a competition team setting
2) Provide a through example of proper DFMEA on the custom P3 Motor for EcoCAR 3
3) Set a recommended threshold for action items on competition style teams
4) Prescribe recommended actions to reduce motor systems risk
5) Recommend an implementation strategy for all phases of the design process in a team setting

The purpose of this thesis is to develop and provide an easy-to-understand and implement DFMEA strategy for multiyear competitions through the in-depth look at a custom motor DFMEA. While DFMEA has been around for decades and various methods are applicable, the main goal of this model will be to develop a DFMEA strategy that is easily implemented and managed by students on both a system and design level. The result of this work is an accurate DFMEA for the P3 motor with risks exceeding a defined threshold addressed and actions recommended to lower their risk. This example will provide understanding to how component selection and design decisions effect the team goals, customer requirements, and overall success of the vehicle. The implementation of the various forms of FMEA throughout the VDP and allowing FMEA to be a living document for all component and vehicle systems ensure project timing and success.

2 Literature Review

2.1 Background and Application of FMEA

Having published "Failure mode and effect analysis" in 2003, Stamatis aims to provide detailed and thorough examples for the reader to effectively apply FMEA in a wide array of settings from the initial theory of FMEA to final execution. A large emphasis is placed on defining the customer and understanding customer requirements. The customer will be unique to the specific application of the FMEA and there are several customers for one component at any point in the development and design. Stamatis begins by explaining the need of FMEA with respect to the legal repercussions and the issues that arise from failing to comply with governing regulations. Leading from there, FMEA as a concept is defined and the common terms are explained allowing for clear understanding among all persons involved in creating the FMEA. Stamatis defines FMEA as "an engineering technique used to define, identify, and eliminate known and/or potential failures, problems, errors from the system, design, process, and/or service before they reach the customer". The importance of team mechanics for FMEA are then heavily emphasized before Stamatis defines the five separate levels of FMEA being systems, design, process, service, and machine FMEA. The electromechanical, computer, semiconductors, medical devices, and the automotive industry are all analyzed to see the specific implications of FMEA for each respective sector.

FMEA may take two distinct courses of risk evaluation, the first being the use of historical data. Looking at previous products of similar purpose and evaluating warranty data, customer complaints, or any other applicable information allows the FMEA team to gain important insight into potential failure modes. Secondly, modeling and simulations in conjunction with statistics and reliability engineering can be used to identify potential failure modes. This thesis will draw heavily on Stamatis' definition of customer requirements as "the courts, regulatory agencies, industrial standards, customer desires, and internal engineering requirements." Concluding the introduction to FMEA is an example of Ford FMEA flowchart emphasizing the continual maintenance of a FMEA at the various phases of the product development process. A FMEA should be started when any new system, product, design decision, or process is initiated or when a previously existing system, product, design, or process is modified.

The three components that help define the priority of failures are the occurrence, severity, and detection. A scale of 1-10 is recommended for evaluating each of the three components. While a scale of one to five may be easier to work with, it does not show fine enough fidelity to separate failure modes and establish a threshold for redesign. Similarly, any scale above 10, while being more accurate can tend to become more difficult to agree upon among the FMEA team and becomes cumbersome. In describing each of these three components, they may be qualitative and/or quantitative. For the purpose of this thesis, whenever possible both methods will be used to provide clear ranking systems for use in future years.

After having described the various aspects of a FMEA, Stamatis then explains the importance of FMEA in the automotive industry. As with all industries and increasing regulations, a need for an actionable process is required to continually improve "so much so that Six Sigma methodology, Advanced Product Quality Planning, Tooling and Equipment (TE 9000), ISO 9000, Qs-9000, and ISO/TS16949" have all explicitly named FMEA as a required methodology for product improvement. Within the automotive industry there are eight types of FMEA that may be conducted: System, Design, Manufacturing, Service, Environmental, Machinery, Software and attribute. This thesis will emphasize only the DFMEA. Stamatis establishes that FMEA in the automotive industry is required when either the customer becomes more quality conscious, reliability problems begin to become more prevalent, or government and industry regulations become harder to meet (Stamatis 2003). A system FMEA is to begin before the product has ever been approved for design and prototype. After receiving approval the DFMEA should begin immediately and be continually updated through component testing and prototypes.

Stamatis' work was extremely beneficial for the use of this thesis as it provided clear definitions and guides to constructing a DFMEA while allowing the author flexibility in the application of the P3 Motor System to establish HEVT specific requirements and FMEA implementation processes to ensure that FMEA is an integral part of the design for all years and all competitions. Suggested roles are proposed for an automotive FMEA team which were adapted to the prescribed roles as laid out in Section 3.2.

2.2 DFMEA in the Automotive Industry and Future Work

Down published "DFMEA and FTA Applied to Complex Hybrid and Fuel Cell Systems" in a 2011 SAE paper to explain the strategies used to understand system failure modes, from simple to complex, while using DFMEA and FTA. An emphasis is placed on the key to a tested and reliable design is "evaluating potential and past issues, ascertaining and then mitigating the risk that past and future issues will potentially occur". This mitigation of risk is an important exercise that is accomplished through DFMEA and FTA, and becoming of increasing importance in the automotive industry with the rising number of battery electric and hybrid vehicles.

Down begins by giving the history of FMEA and the genesis in the United States military and aerospace applications, leading to the adoption by the automotive industry. The wide spread use of risk analysis for risk prevention in the automotive industry's engineering development process has increased and become more quintessential for major OEMs (Down 2011). This is largely due to increasing levels of technology and complexity of designs (Down 2011). SAE standard J1739 was developed to provide procedures and recommendations for suppliers and engineers on effective development of an FMEA analysis (Down 2011).

A DFMEA captures various levels of risk analysis: system, subsystem, interface/part, and finally component. At the system level, the engineer would take into account all subsystem interactions from a high level. Failure modes at such a high level are often broad reaching and aim to produce areas "which impact the customer or those that would come into close contact with other areas of the design and process". For a complex system such as a hybrid vehicle, Down suggests protocol to advise for the design engineer to begin evaluating at the system level before moving to any lower level. After having defined the level of analysis, a block diagram is used to determine what is to be included in the analysis and the scope. Additionally, a block diagram allows the FMEA team to ensure they haven't overlooked any major system or subsystem level connection. A comprehensive DFMEA is led by an engineer who guides the discussion through every point risk developed. During this discussion, the severity, occurrence, and detection RPN numbers are assigned after coming to agreement amongst the team. The major issue with DFMEA is that individual causes are treated as a single points of failure, and therefore does not show important interdependencies between risks. Once the FMEA team has decided the critical risks that are interrelated, Down suggests evaluating the prescribed area with FTA.

While a DFMEA looks a single point risks, FTA presents the engineer with a method to gain a top down approach to evaluate the design. Standard logic operation symbols are used to communicate the relation between components in a given analysis. FTA starts with a system-level failure and continues until the final point risk is discovered.

Having a bottom-up approach in DFMEA and top-down approach in FTA, software has been developed to provide engineers with a "Failure Net". In traditional risk analysis, functions are related to components and interfaces, but lacking the ability to show as a chain of events. IQFMEA combines DFMEA and FTA in a way that changes the typical component to component discussion to a systematic discussions (Down 2011). The result of IQFMEA is the failure net which gives the engineer perspective from the vehicle or system level failure and simultaneously see all of the lower level failures that could have led to the system level failure.

Down's discussion of FMEA, FTA, and the newly developed software IQFMEA are applicable for this thesis. The examples provided being automotive in nature allow for direct comparison of the developed model for the P3 Motor System. EcoCAR 3 has the goal to simulate the GVDP in an academic environment. In order to do so a firm understanding and application of DFMEA must be accomplished. While this thesis will not involve a FTA or IQFMEA, the author recommends that in future years, both avenues are explored to decrease the known and potential risks with vehicles that are growing in complexity and increasing safety standards.

2.3 SAE J1739 development by the OEMs

In the article "Why SAE J1739" by Carlson, McCullen, and Miller the emphasis is on improving safety, quality, and reliability of their products through FMEA. Each of the writers came from one of the "Big Three", General Motors, Chrysler, and Ford. Prior to the development of J1739 each of the OEMs had slightly different ways of performing DFMEA. Due to the subjective and relative nature of FMEA, any minuet differences in the manner in which two separate FMEA are performed will lead to significant differences in ranking of failure modes. J1739 provides common and detailed information into a common FMEA form to ensure that the "whats" and "hows" of a risk analysis are not lost. The DFMEA and PFMEA forms were developed with great detail to ensure that the FMEA could be carried out successfully by providing common definitions for the terminology needed in FMEA. Terms such as failure mode, effects of the failure, and causes were all given common definition. The single largest contribution of J1739 is the developed ranking tables with detailed criteria to allow common ranks internally within one company but also between the OEMs and suppliers. Prior to J1739 the severity and detection ratings had five criteria descriptions for 10 possible rankings.

This article is beneficial to the thesis scope as the author is attempting to develop a common FMEA procedure that can be used by students in an academic competition setting without the need for overly complex additions. The foundation of the ranking systems for severity, occurrence, and detection were taken from J1739, providing the ground work for expansion and further explanation when needed for hybrid vehicle systems. This article also emphasizes the critical nature of FMEA being created, performed, and analyzed as a team. This mentality was carried out through the manner in which the Motor System DFMEA was conducted for this thesis.

2.4 Risk analysis is not easily and commonly incorporated

Ward and Chapman published "Extending the use of risk analysis in project management" in 1991 in an effort to address the role of risk analysis in project management. First a definition of a risk analysis is given that includes identification, appreciation, and management of project risks (Ward and Chapman 1991). The roles of risk analysis for project management are evaluated. Barriers to risk analysis in project management are identified and arguments are given to overcome these difficulties.

For any given project the development and successful execution can be an uncertain and difficult process. All of these are largely based upon the complexity, scale, novelty, and technical innovation involved. The necessity for project management skills that will face these uncertainties has been the catalyst for the development of management-science techniques in risk management. While the benefits of risk management are inherent in safety and reliability of a product, it was not met with equal incorporation into industries. Ward focuses on given an all-encompassing definition of roles for risk analysis, then considers how the definition might need to be altered for multi-party projects. Concluding with a discussion of the possible reasons why risk analysis isn't as widely used as the author would have assumed.

The most notable approach was the Synergistic Contingency Evaluation and Review Technique (SCERT) which was developed in the 1970's by BP International. SCERT was created to manage billion-pound sterling projects and ensures comprehensive risk identification, understanding, and management (Ward and Chapman 1991). Risk analysis is then assumed to be defined by the SCERT approach or similar. Ward then categorizes the four roles for the treatment of project risk. Upon receiving the approval or specifications for project, an initial risk analysis should be carried out with sufficient level of detail, alternate technology choices for simpler integration, system level sources of risk and their responses, any uncertainty in the project, methods for increase the efficiency of the project, and check the expected-cost/risk balance to ensure project worth. The outcome of the first role in risk analysis is an unbiased decision to accept or reject the project based upon a threshold level of risk. The second role of risk analysis is to perform a more in depth risk analysis to ensure project validity. This thesis aims to encapsulate the first two roles of risk analysis by providing an in depth FMEA for the highest-risk system in the powertrain selected by HEVT. The final two roles are cyclic in nature, allowing project management to continually go back and evaluate at any point in the development process the current level of risk and if that level is too high to continue with the project questions such as "is it worth a slight increase in expected cost to significantly reduce the risk?" (Ward and Chapman 1991).

Risk analysis when involving more than one organizing and developing parties requires increased attention to the processes in place. Each party may perform their own risk analysis leading to unintended bias and skewed risk for the other parties involved. The principal-agent relationship brings about two primary problems, the agency problem, and the risk-sharing problem. In the prior, the goals of both parties conflict, whether it be for cost of development and manufacture or timing of various aspects of the process. The risk-sharing problem stems from differences in evaluating and assigning each item risk, which can lead to miscommunication on the importance of varying aspects throughout the development. For the thesis work, remaining in constant communication with the motor manufacturer is pivotal to ensuring HEVT risks are properly conveyed and understood, as well as the industry sponsor risks while design is underway.

Ward concludes with a strong belief that risk analysis has not become as integral in all industries as necessary and poses several reasons why companies and developers may have neglected risk analysis. The first is lack of awareness in which the project owner is simply unaware of the benefits of risk analysis. Similarly, a lack of expertise on the project owners' account may render the manager unable to carry out sufficient analysis. The project manager may also consider risk analysis largely unnecessary and desires to avoid "paralysis by analysis" (Ward and Chapman 1991). Insufficient timing to carry out the analysis and the difficulty to do so are also considered as reason why risk analysis may be avoided. The project manager may also have a mistrust in the ability of the analysis to produce realistic results or be under the assumption that the risk management will be handled by another party.

Ward suggests that all of the expected reasons for risk analysis avoidance lie in a lack of understanding of the true contribution of risk analysis to a company. This thesis aims to address these reasons by producing a method and example that allows students to understand the benefit and necessity of risk analysis in any project, and the steps by which it can be implemented into a student competition or design setting that is easily manipulated and used. Wards findings for reasons why companies fall away from risk analysis coincide with this author's belief of why students in academia do as well – with an increased emphasis on the lack of understanding of the potential benefits.

2.5 A case study of FMEA in automotive vehicle applications

Vinodh and Santhosh published "Applications of FMEA to an automotive leaf spring manufacturing organization" to report the application of FMEA to an automotive leaf spring manufacturing process. Throughout this case study, FMEA was used as a decision making tool to help the authors prioritize corrective actions to enhance the system performance by reducing the component failure rates (Vinodh and Santhosh 2012). The findings of this study supported the use of FMEA as a reliable method for design improvement and were carried out by the development of a DFMEA and a PFMEA.

With the rise of companies and increasing competition, manufacturing organizations have been forced to improve upon their quality control techniques. FMEA has been developed and used to improve designs and clarify basic customer requirements. Engineers use FMEA as a contemporary tool "to depict in a structural and formalized manner the subjective thinking and experiences" (Vinodh and Santhosh 2012). Vinodh states that the primary benefit of FMEA is the improvement of product quality which in turn ensures customer satisfaction. The three inputs considered in FMEA are the severity, occurrence, and detection. The resultant product of these three inputs are a risk priority number, or RPN. A higher RPN value means the higher the expected chance for that item to fail and requires action from the team to address the root cause. The adoption of FMEA is essential for good adaptability to problems of reliability and performance with in the automotive industry.

The primary manufacturing process involved in the leaf springs is the shearing operation, which is required for the dimensioning of the springs (Vinodh and Santhosh 2012). The DFMEA focuses on the design of the product that is intended for the end user. The tasks required for the establishment of a DFMEA include: gathering a team, agreeing upon an analysis scope, generation of system and component level block diagrams, and finally compiling the product functions and specifications. The DFMEA form allows for the proper documentation of results including recommended actions items. The severity of a risk is the value associated with the most serious effect for a given point failure (Vinodh and Santhosh 2012). "Occurrence is the likelihood that a specific mechanism will occur resulting in the failure mode within the design life" (Vinodh and Santhosh 2012). The value assign to occurrence is relative based upon the design life for a given component and may vary for the entire system. Detection is a rank of the current method in place to identify that a failure has occurred. A low detection ranking should not be the result of a low occurrence rating. For a properly functioning system to be adequate, the system must be able to detect low-frequency failures. The various rankings for S, O, and D, should constantly be revised as new methods to reduce any or all of the inputs are established.

In order to properly rank numerous failure modes an agreement of the scale is required. Vinodh prescribes a ranking system of 1-10 with criteria at each integer for Severity, occurrence, and Detection. These scales were used to develop the DFMEA for the leaf springs. Upon completion of the DFMEA, a PFMEA can begin with the development of a list of process intent. A flow chart is generated to illustrate the general process. A major disadvantage of the RPN ranking method is the inability to note relative importance among S, O, and D. Varying combinations of S, O, and D can produce identical RPN but may in fact have drastically different design implications. The PFMEA ranking scales are all 1-10 as with the DFMEA but the criteria and description have been changed to account for the setting of a process.

As a result of the DFMEA and PFMEA the design of the leaf springs was improved by specifying the raw materials used for cast products, the temperature measurement technique, and refined operating temperature limits at the plant. The reduction of failure due to DFMEA and PFMEA was attributed to a 10% decrease in design mishaps, a 15% increase of improvement in productivity, a 10% increase of improvement in quality, and a 20% reduction in rejection rate and time loss (Vinodh and Santhosh 2012).

The work presented in this article is extremely relevant to this authors thesis in that the approach and purpose align near perfectly – to present a case that shows and validates the importance of FMEA in a design setting while providing guidelines for implementation into various settings and projects. The primary difference is in the ability of Vinodh to obtain significant results from implementing recommended design changes whereas this thesis will pose suggested design changes for future work and similar projects to the P3 motor. Additionally, this thesis will provide direct correlation of point failures to competition related scoring for customer requirements and overall placement of the team in competition standings.

2.6 Summary of Literature Review

This literature review discusses several related works which provide confidence to FMEA as a whole, the methods by which FMEA is most effective, and contribute to the implementation of the model developed through this thesis. Stamatis thoroughly detailed the key terminology and steps of a successful FMEA. These include the increased emphasis on defining the customer and understanding customer requirements and how the end result of a successful FMEA is to have a product that was designed to meet all customer requirements without sacrificing the safety of the process and quality of the product (Stamatis 2003). The emphasis on safety stems from each products regulatory government standards, which themselves serve as a customer for the FMEA to consider. The theory of FMEA and overall importance of team is then discussed and group dynamics are explained to allow for the better management of FMEA sessions. Concluding from Stamatis is the overview of the necessity and role of FMEA in the automotive industry that will increasing regulations so much so that Six Sigma methodology, Advanced Product Quality Planning (APCP), Tooling and Equipment (TE 9000), ISO 9000, Qs-9000, and ISO/TS16949" have all explicitly named FMEA as a required methodology for product improvement(Stamatis 2003). Leading off of Stamatis' work, Down introduces the implementation of FMEA into the automotive sector and overall implications of SAE Standard J1739. Down discusses DFMEA and the various levels of risk analysis should be taken: system, subsystem, interface/part, and component. The development and importance of a block diagram for looking at the high level system, and all subsystem level components is stressed as it allows the FMEA to determine the scope of the analysis before starting. The inherent flaws of a FMEA are revealed due each cause being treated as a single point of failure, and therefore is unable to properly correlate important interdependencies between risks (Down 2011). The proposed counter part of the bottom-up approach of FMEA is to also develop a top-down viewed FTA to better relate all developed risks for the analysis.

After having the general theory and flaws of FMEA, Carlson's explanation of the importance of J1739 as a standardized method for applying FMEA in the automotive industry gave support for the development of a method for a varying application of an academic setting. The development common terminology that is specific to the application, design, and customer for entire company or organization was also discussed as one of the primary contributions of J1739 to FMEA. The largest contribution from this article is confidence in basing this thesis ranking scales upon those developed for severity, occurrence, and detection. Carlsons' promotion of J1739 concluded by emphasizing the importance of team dynamic (Carlson, McCullen et al. 1995). Following these three articles Vinodh provided a similar study of an FMEA performed on automotive leaf springs. This article allowed for the validation and comparison of results found from the P3 motor study conducted. Vinodh also gave specific examples for the theories discussed by Stamatis, Down, and Carlson for team development, determining the scope of the analysis, and finally the generation of component level block diagrams. The disadvantage of FMEA RPN ranking method being unable to note relative importance among severity, occurrence, and detection. Varying combinations of the three ranking criteria can result in identical RPNs, while having different design implications (Vinodh and Santhosh 2012). This understanding was adopted when the author set thresholds for the motor system.

Finally Ward gives tangible evidence and reasons behind why risk analysis is not widely incorporated to the level that most designs and processes would benefit. The management behind risk analysis and the importance of design completion and integrity is discussed through addressing commonly given reasons why he believes risk analysis is avoided. The first being the company or organizations lack of understanding of the benefit risk analysis brings to the design. Secondly, when the management does not believe the risk is worth the time investment, risk analysis is avoided. The project manager may wish to avoid “paralysis by analysis” (Ward and Chapman 1991). Management may also lack the expertise needed to lead a risk analysis that would produce any usable information for risk mitigation. The amount of time required and overall difficulty of risk analysis are discussed as two of the largest reasons that management may avoid any form of risk analysis. This discussion by Ward emphasizes the desire of this thesis to develop a FMEA method that can be replicated and implemented easily by management and members to ensure the benefit of risk analysis is realized.

As the literature proves, the method and approach of this thesis are supported and highlighted in various articles for several years. The ability for management, employees, students, and any one working on FMEA to effectively understand the benefits, develop a proficient FMEA team, and carry out the living analysis is and will be relevant for years to come. This thesis will adapt work and theories that have been developed by bridging the lack of experience with a thoroughly documented process for FMEA implementation, specifically for advanced vehicle technologies and the VDP.

3 DFMEA Terminology, Team Theory, and Definitions

The DFMEA execution described in this thesis has been developed as an Excel based tool to aid organization efforts in achieving the VTS included in Table 1-2. The basis for a majority of the methods were derived from Stamatis and the SAE Standard J1739. At different times a combination of the two will be used to better encapsulate the unique environment of a timed competition without losing the intent behind the specific method of evaluation. These definitions will allow the user of the model to understand the various aspects of the model needed for a complete FMEA.

3.1 The DFMEA Team

DFMEA is designed to be "a catalyst to stimulate the interchange of ideas between functions affected" (Stamatis 2003). For this reason DFMEA can only be effectively completed with a selected team that represents the collective areas of the entire organization. The importance of the team dynamic for FMEA cannot be understated and therefore this thesis proposes and tested the implementation of the following roles for a DFMEA Team:

1) Designer
2) Drawings for Manufacture
3) FMEA Engineer
4) Interface Engineer
5) Validation Engineer
6) System Safety Manager
7) Lead Faculty Advisor
8) System Safety Advisor
9) Supplier Representative

The progress of the DFMEA as well as the focus of the specific meeting will determine the required members to attend. The only required member at each meeting is the FMEA Engineer as they are the team member responsible for continuity and consistency between all FMEA processes. The FMEA engineer should facilitate the discussion and manage the time wisely as a thorough DFMEA can take hours to days to develop, proper planning is important to respect the time of those members attending and ensuring that the quality of the results found are sufficient. The FMEA Engineer is the most critical role on the FMEA team and their sole responsibility in the organization should be FMEA. This is a new leadership position that should be assigned at the onset of each year and individuals be training underneath the current FMEA engineer to replace the current FMEA engineer upon leaving the position. For a majority of DFMEA meetings the designer of the component or system should be present to give and receive critical feedback from other members of the team that may be downstream of design decisions. When the time comes to consider the various interfaces of the system being analyzed, the interface engineer should attend. In a setting such as HEVT the interface engineer may be anyone working on the high voltage or low voltage wiring harness, the CAN wiring, or the mechanical connections between components. The team member responsible for the drawings for manufacture should be present to ensure that the design requirements and specifications listed for the function of the failure mode are correct and match that which have been developed for drawings. The validation engineers' responsibility is to weigh in on the potential failure modes impacts on the testing of the component system. Bench testing may be in controller SIL or HIL, or mechanical testing that can be completed before any in vehicle testing is started.

This author recommends that for any milestone DFMEA meeting, whether the first for a major system or component, or one with a supplier representative that the Systems Safety Manager and Lead Faculty advisor are present. Upon completion of a major milestone the FMEA engineer and Systems Safety Manager should review the data with the Systems Safety Advisor to ensure validity of the data. The only required circumstance for all members to be present is when the FMEA team intends to set thresholds for RPN or SO.

DFMEA cannot and should not be attempted by any one individual as doing so will lead to inherently biased results. The downside of doing FMEA as a team is the increased duration of time required to develop, the disagreements between FMEA team members over ranking values, and the need to develop common definitions for every single cell in the worksheet. The role of the FMEA Engineer in these events of disagreement is to encourage all present members to come to a consensus. This concept of a consensus within DFMEA is critical in understanding the RPN values output at the conclusion of a DFMEA. While an individual or group of individuals may not completely agree with the ranking, definition, criteria, or any aspect of a DFMEA – the entire DFMEA is to be halted until there is 100% support from all DFMEA team members. The following three ideals must be formally acknowledged in order for consensus of any given item on a DFMEA (Stamatis 2003):

1) 100% participation from members present in the meeting
2) 100% Commitment from members to support and move forward with decision
3) Active admission from present members that the majority is not always correct

The three ideals ensure that a true consensus is reached for the DFMEA and that moving forward there is consistency which produces the most accurate results.

3.2 FMEA Team Meeting Structure and FMEA Implementations

3.2.1 FMEA Team Meeting Structure

For FMEA to be effective, the process must be repeated frequently enough to incorporate the living design changes without being over bearing on the members inhibiting their ability to progress on the design itself. Having experienced all years of AVTCs this author recommends that all fourteen major systems of the vehicle should meet for FMEA updates bi-monthly with the FMEA Engineer. These meetings should be no more than two hours in duration to respect the team members schedule and encourage productivity and good use of the meeting time. The FMEA engineer would then be meeting for a maximum of 14 hours each week. Table 3-1 displays the recommended meeting schedule based upon complexity of the systems and personnel required.

Table 3-1: Recommended meeting schedule for effective vehicle SFMEA

Weeks 1 & 3	Weeks 2 & 4
Conventional Systems	**Electric Systems**
Engine	Electric Motors
Transmissions, Differential/Half shafts	Energy Storage
Internal Combustion Engine Cooling	Power Electronics Cooling
Fuel System	Hybrid Vehicle Supervisor Controller & Stock ECU Interface
Suspension, Handling, Brakes	HV Battery Charger
Exhaust + Intake	LV Wiring Harness
	CAN Controlled Pumps/Fans/Components

The weeks have been separated based upon whether or not the vehicle system is more closely related to the conventional or the hybrid component operation to allow for consistency and order to the meeting arrangements. Changes may need to be accommodated based upon member schedules and their involvement in more than one vehicle system. The FMEA Engineer should prepare in advance the goal and desired output of each meeting and communicate both to the members present at the start of each meeting. The meetings should be scheduled in advanced and be in the same location, on the same day and time when possible.

Team member attendance should be tracked on a form such as shown in Table 3-2. Tracking of attendance allows for the analysis of which members areas required more discussion and show specific functions that need to be addressed within the given vehicle system. For example, if for a given DFMEA the team member responsible for the drawings for manufacturer was required at more meetings than expected, the team as a whole should pay more attention to the necessity to increase efforts on drawings to mitigate the issues arising requiring the team members attention.

Table 3-2: Team Member Attendance Form Except

Team Member Name	E-mail	Responsibilities	Date 1	Date 2	Date 3
		Designer			
		Drawings for Manufacture			
		FMEA Engineer			
		Interface Engineer			
		Validation Engineer			
		Supplier Representative			
		System Safety Manager			
		Lead Faculty Advisor			
		System Safety Advisor			
		Project Manager			

3.2.2 FMEA Implementation into the Vehicle Design Process

At the onset of Year 1, HEVT was informed that the vehicle platform for EcoCAR 3 would a 2016 Chevrolet Camaro. Prior to any powertrain being selected for the remainder of competition and in-depth Consumer Market Research Report was conducted to determine the target market for the Camaro. Upon determining the target market to be the Forward Thinking Patriots (FTPs), a feasibility study was conducted to propose five powertrain configurations. During this stage of the VDP is when a SFMEA should be developed for the vehicle. During this time the intent of the SFMEA should be to properly define the customer and clearly describe the customer requirements as quantifiable values. The SFMEA will guide the team to selecting the proper VTS as shown in Table 1-2 by directly relating system risks and potential failures to the overall effect on the customer requirements. The levels of customers and specified requirements will be discussed thoroughly in section 3.3. Once having successfully defined and completed a SFMEA for each major vehicle system defined by the team the SFMEA can begin to translate to a DFMEA.

The DFMEA for a given four competition should begin immediately following a comprehensive SFMEA. DFMEA is projected to take place at the end of the first year into the beginning of the second year and be refined throughout the entire year. The DFMEA takes the failure mode causes developed in the SFMEA as new specific failure modes for a given vehicle system. The major result of the DFMEA is detailed component requirements and specifications to meet the vehicle technical specifications established through the SFMEA. During the DFMEA stage if any significant design changes are made, the repercussions must be reflected in the SFMEA and PFMEA. The root cause identified within the DFMEA is then evaluated as the failure mode for the PFMEA. The PFMEA allows the team to develop and implement the preventive actions to ensure component functionality and integration into the vehicle before the 99% VDP vehicle milestone at the end of the final year of the competition. The Figure 3-1 describes the translation from a SFMEA to a DFMEA and the final into a PFMEA for a given four year competition such as EcoCAR 3.

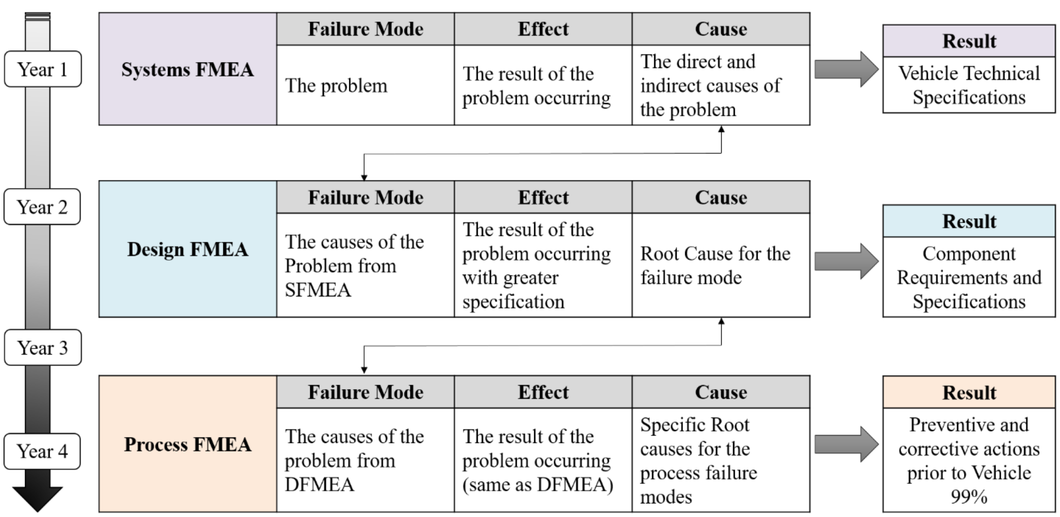

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Figure 3-1: Evolutionary process of FMEA adapted from Stamatis (2003)

FMEA is cyclic in nature and at any point if the SFMEA, DFMEA, or PFMEA need to be reevaluated it is in the best interest of the team to do so and adjust all FMEA documents to reflect any changes in any stages downstream of the correction. A consensus from the component system FMEA team must be met in order for a phase of FMEA to move into the next. This point signifies the groups satisfaction with the level to which the system has been analyzed or the point in time which the particular FMEA must be complete.

At the onset of the competition and early on in each component system FMEA team meeting, dates for the tentative completion of each phase of FMEA should be set to keep the team mindful of necessary progress. These dates may be consistent for various vehicle systems, but can vary drastically depending on the amount of information available at the time or the prior experience the current team has with similar systems. The phase change dates should be made with the every FMEA Team member present as these deadlines will drive the progress relevant to each member.

3.3 Defining the Customer

The primary focus of DFMEA is to reduce the risk and improve the customer satisfaction. In order to properly determine what requirements should be considered for a given system the FMEA team must define the customer for each DFMEA generated. This thesis proposes that there are four specific customers that should be defined before an accurate DFMEA can be performed. The definition of the customer is critical to properly defining all aspects of a DFMEA from the failure modes to the rankings assigned for Severity, Occurrence, and Detection. The first customer is the end user. This individual for EcoCAR 3 will be Forward Thinking Patriot as the defined target market for HEVT (HEVT 2014). The analysis must be performed keeping the desires of the market in mind and how potential failure modes may be recognized by the end user. For the end user the HEVT Team Target VTS from Table 1-2 are to be considered the quantifiable metrics that component system designs must meet. The second customer is defined as the governing organizations that enact regulations for safety, whether that be of the user or of the environment. For competitions such as EcoCAR, Argonne National Labs (ANL) and (General Motors) sets forth Non-Year Specific Rules (NYSR) that are to be considered the governing organizations. Governing organizations requirements are quantified for this project as meeting safety and environmental standards in the automotive industry. These customer requirements may not directly impact or even be noticed by the end user but are required for the intermediate customer. For components and systems that require supplier involvement on a design level, the supplier is also to be considered a customer. The requirements the supplier has for the component must be met in order to ensure proper design and manufacture of the system. Finally, the last customer is the internal customer. The internal customer is anyone within the team whose component system or position is affected by or dependent upon the current vehicle system undergoing DFMEA. During the early stages of a DFMEA when the final designs have yet to be finalized, the fabrication engineer should be considered the internal customer as the design and drawings for manufacture directly impact the work that is to be performed by them and these desires should be accommodated. The customer requirements for all three levels should be constantly assessed to determine if the current design meets all requirements and if the design fails to meet any requirement, actions should be taken to ensure customer satisfaction.

3.4 FMEA Naming and Numbering

Contained within the very beginning of the DFMEA worksheet are the FMEA Name and Number. The FMEA name is to be descriptive enough to be widely understood by any member throughout the entire company, regardless of their involvement in the FMEA process. This name is to be selected by the FMEA leader and agreed upon by the FMEA

Team. Secondly, the FMEA number has been an addition by the author to allow HEVT to systematically track and store future FMEA for various systems, components, and parts. Table 3-3 shows an example FMEA Name and Number.

Table 3-3: Example FMEA Name and Number Convention for Energy Storage System

FMEA Name	EcoCAR 2 Energy Storage System
FMEA No.	S_EC2_4_2013-11-22-1413_11_LWS

Table 3-4 shows the user inputs that result in the above FMEA number for which all systems and components within the vehicle are able to be sorted.

Table 3-4: Example FMEA Name and Number Convention for Energy Storage System

FMEA Type	System
Competition	EcoCAR 2
Component System	Energy Storage System
Creation Date (YYYY-MM-DD-TTTT)	2013-11-22-1413
Revision	11
Author (Initials)	LWS

Upon receiving the user inputs from Table 3-4 the model outputs the proper FMEA number and automatically populates the proper cells throughout the model to ensure consistency and increase the ease of user interaction. Figure 3-2 displays the file naming convention which is automatically generated by the model.

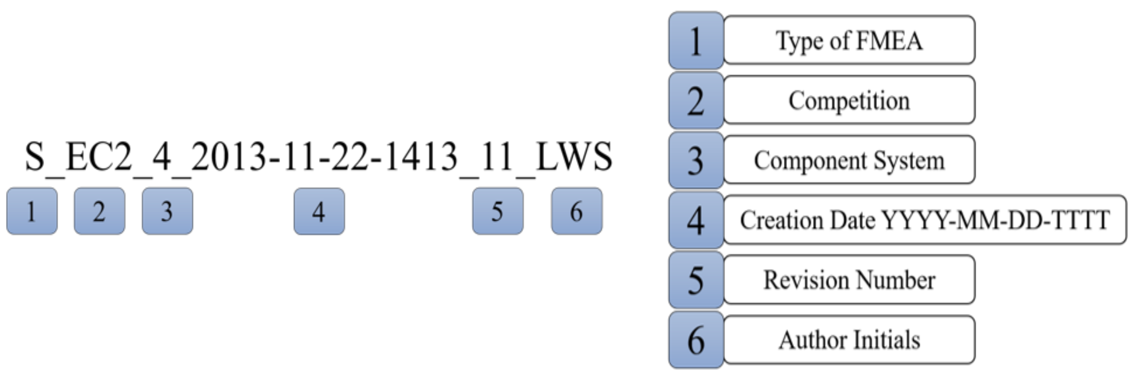

Figure 3-2: Example FMEA Number Convention with Explanations

The FMEA engineer will select the FMEA Type, Competition, and Component System from drop down menus which give another level of consistency in naming and tracking of vehicle FMEA. The vehicle was broken down into thirteen high level component systems to guide FMEA at any point in time in a competition. These thirteen types and their associated component number can be found in Table 3-5.

Table 3-5: Component Numbering

Component System	Component Numbering
Engine	01
Electric Motor Systems	02
Transmissions, Differential, Half Shafts	03
Energy Storage Systems	04
Fuel System	05
Power Electronics Cooling	06
Internal Combustion Engine Cooling	07
Exhaust & Intake System	08
Suspension, Handling, Brakes	09
Hybrid Vehicle Supervisor Controller & Stock ECU Interface	10
HV Battery Charger & DC/DC Converter	11
CAN Controlled Pumps/Fans/Components	12
LV Wiring Harness	13

3.5 DFMEA Column Descriptions

The core of the DFMEA is contained within 13 areas that presented as columns. This model follows the J1739 Standard and the areas are as follows:

1) Subsystem
2) Part/Interface
3) Function
4) Potential Failure Mode
5) Potential effects of Failure
6) Severity
7) Potential Cause/Mechanism of Failure
8) Occurrence
9) Current Design Controls – Prevention Method
10) Current Design Controls – Detection Method
11) Detection
12) Risk Priority Number
13) Recommended Actions

The remainder of this section will give the specific definitions chosen that will apply directly to HEVT and the scales with examples for Severity, Occurrence, and Detection. The end result are definitions that allow DFMEA to be performed on both mechanical systems and controller requirements. For this reason there separate mechanical/electrical and Controls examples for select columns.

3.5.1 Subsystem

The subsystem for this DFMEA is defined as the specific assembly of components. These subsystems will collectively make up the entire system being analyzed by the FMEA team.

The level of specificity of the subsystems is largely dependent upon the level of experience with the system by the team. The defined customers and suppliers should be consulted when the subsystems are being established to ensure that no significant subsystem is missing or information is incorrect. The subsystem is one area where there will be significant difference between the mechanical components and a controller requirement. Mechanical subsystems are concerned with the structural integrity, mechanical connections, wiring proficiency, and overall design of the physical component. Controller related subsystems are dedicated to those whose risks are primarily in the development and communication with the controller or module in question. Table 3-6 shows an example of subsystems to be considered when performing DFMEA on the ESS.

Table 3-6: Subsystem Category

Subsystem	Mechanical or Controller
Battery Modules	Controller
Current Shunt Module (CSM)	Controller
Electromagnetic Interference Filter	Controller
Energy Storage Control Module	Controller
Energy Distribution Module	Controller
Manual Service Disconnect	Controller & Mechanical
ESS Vehicle Mounting Structure	Mechanical
ESS Frame	Mechanical
ESS Enclosure	Mechanical
ESS HV Wiring	Electrical
ESS LV Wiring	Electrical

The ESS enclosure and mounting structures are the only subsystem classified as mechanical due to the analysis being confined to the structural integrity of the ESS. The remaining subsystems are to be developed by the ESS FMEA team. The subsystem level is to be analyzed first as it allows the entire FMEA team to break down the entire system selected into which parts are to be analyzed, ensuring nothing is overlooked.

3.5.2 Part/Interface

The part for this DFMEA is defined as the isolated component being analyzed for both the mechanical and controller classified subsystem parts. If engineering drawings exist at this stage, then the drawing number should be included as well to provide more information and consistency throughout the DFMEA process (SAE J1739).

3.5.2.1 Part/Interface Connections

After having established all the parts to be analyzed in the DFMEA, the FMEA team then must determine the method by which all of the parts and components are connected. The team will then define connections used within the respective system being analyzed. Examples of these types of connections are fastener, electrical, crimp, and slip fit. An exhaustive list should be developed to ensure that all connections with the system are represented. An example list and reference number are shown below in Table 3-7.

Table 3-7: Component connection types within an example subsystem

Connection Reference #	Connection Type
0	No Connection
1	Fastener
2	Electrical
3	Crimp
4	Slip fit

After having developed the list of possible connections a matrix of component connections is to be generated showing the interface relationship between the previously established parts and components. An example of a connection matrix is show in Table 3-8.

Table 3-8: Example component interfaces and connections for a given analysis

Component	Component A	Component B	Component C	Component D
Component A		2,3	0	4
Component B	2,3		0	0
Component C	0	0		1
Component D	4	0	1	

3.5.2.2 Block Diagram Generation

From Table 3-8 the FMEA team is able to develop a component level block diagram for the system being analyzed. Organization of the block diagram becomes ever more important as the complexity of the system and number of components increase. A preliminary block diagram may be beneficial in the generation of the connections within Table 3-8. The block diagram and connection matrix should then both be updated as new information is available. An example block diagram is provided in Figure 3-3 for the component interfaces developed in Table 3-8.

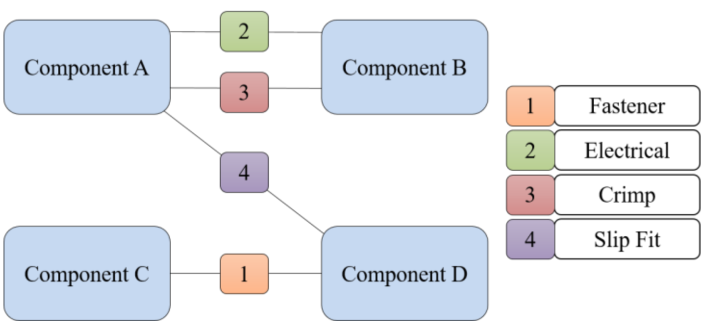

Figure 3-3: Block Diagram for Example Component Interfaces

From the block diagram the design functions and potential failure modes are more easily generated with the assist of being able to visualize the various connections. As with every aspect of FMEA, all connections are to be developed before the FMEA Team moves onto developing the design functions of parts and components. Completing "one column at a time" is a way to ensure that every part of the design is considered before the team starts trying to develop the RPN for a signal risk item. This structure also allows for the most orderly way to develop the DFMEA worksheet and limits the amount of revision in each column after the initial creation.

3.5.3 Design Function

The design function for this DFMEA is defined as the task that the system, design, process, component, subsystem, or service must perform. This function must be clearly articulated and understood by all individuals working on the system (Stamatis 2003). The function of the part is to be analyzed to meet the design intent and any information regarding operational ranges such as temperature, pressure, and power limits should be included. For parts with more than one function and those functions with various failure modes, the functions are to be listed separately on a new risk line (Standard 2002).

The design functions of mechanical part such as the Motor Stator Slot insulation is to insulate the stator windings from the core. However, for the controller part of Communication Input the associated function is that the inverter shall receive a PDO timeout message from the motor. The design functions for those parts that are specific to inverter communication have been created as the controller requirements used when developing the ways in which the hybrid vehicle supervisory controller (HVSC) will interact with the inverter.

3.5.4 Potential Failure Mode

The potential failure mode for this DFMEA is defined as the physical manner in which the failure occurs (Stamatis 2003). This failure is the inability of the design to meet specified design intentions. Theses failures should be all inclusive including any previous failures associated with similar functions or parts, or any potential failures. Failure modes, as with all the areas of a DFMEA should be created with a team to ensure clarity across various disciplines and that nothing is missed.

The potential failures of a mechanical part and a controller part are similar in the sense that they should be as specific as possible for the given failure mode. However there will be circumstances when a failure mode may be as simple as failing to perform the designed function. The failure modes assigned to the various design functions are the result of a FMEA Team brain storming and thorough review of things gone wrong in similar situations from past competitions. Examples of specific failures contain words such as:

- Open Circuit
- Sheared/Broken
- Eccentric

Additional system level failure modes exist such as component and subsystem cost and timing. For this thesis focusing primarily on DFMEA the cost is not detailed and assumes proper SFMEA is conducted to provide a budget and timeline under which the system being analyzed must meet.

3.5.5 Potential Effects of Failure

The potential effects of failure for this DFMEA are defined as the outcome or consequence of the failure (Stamatis 2003). These outcomes should be considered when possible at first a local level, then a global level. The effect of the failure should always be described as what would be perceived by the customer. The customer may however be an internal customer of the manufacturing engineer or the end-user themselves. The effects should be written for a specific customer. When considering a motor system and more specifically the motor shaft, the local level effects of an alignment failure are vibration and the decreased performance of motor. However on a global level the decreased performance of the motor and the severity of the vibration may lead to decreased or completely removed vehicle operability. Examples of potential effects are noise, instability, operation impaired, and reduced operation life.

3.5.6 Severity

The severity for this DFMEA is defined as the analysis of the significance of the effect. The severity should be assigned to the effect alone, not the potential failure mode or relevant system. The severity scale show in Table 3-9 is use during meetings to rate the severity of every potential risk developed on a scale from one to ten.

Table 3-9: Severity Rankings adapted from Standard (2002)

Rating	Severity	
	Criteria	**Category**
10	Potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation without warning	Safety and/or Regulatory Compliance
9	Potential failure mode affects safe vehicle operation and/or involves noncompliance with government regulation with warning.	
8	Total Loss of primary function (vehicle inoperable, does not affect safe vehicle operation)	Primary Function – Vehicle Operation
7	Degradation of primary function (vehicle operable, but at reduced level of performance)	
6	Loss of secondary function (vehicle operable, but comfort / convenience functions inoperable)	Secondary Function – Motor System Operation
5	Degradation of secondary function (vehicle operable, but comfort / convenience functions at reduced level of performance)	
4	Appearance or Audible Noise, vehicle operable, item does not conform. Defect noticed by most customers (> 75%)	Annoyance
3	Appearance or Audible Noise, vehicle operable, item does not conform. Defect noticed by many customers (50%)	
2	Appearance or Audible Noise, vehicle operable, item does not conform. Defect noticed by discriminating customers (< 25%)	
1	No Effect	None

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From this scale, a severity rating of a one is assigned to any risk whose effect is deemed negligible on the specified customer. Using the motor system as an example, any effect whose result is not that of vehicle degradation or inoperability have been rated as an annoyance and vary from two through four depending on the ability of the customer to detect the failure effect. The secondary function for this analysis is the motor system operation. While the motor system is the sole focus of the DFMEA, for the severity rankings, the secondary function is to be viewed in terms of the vehicle operation and is therefore motor system operation. A ranking of five conveys the motor system operation has been effected but not rendered inoperable, where as a severity ranking of six requires the user to rely solely on the internal combustion engine to sustain vehicle operation as the motor system is no longer operable. Once a severity ranking of seven has been reached the vehicle primary function begins to degrade. When the vehicle is no longer operable and both propulsion systems of the vehicle have ceased the severity is assigned at least an eight. At this point, the user is able to retain all safety features and bring the car to a stop without concern for safety or noncompliance with government regulations. Breaching into a severity of nine or ten impacts the user in that the effect directly impacts safe vehicle operation and may or may not give warning prior to the effect taking place. The vehicle may still be operable for a severity ranking of nine or ten, however the safety of the customer is to be of utmost concern and therefore the vehicle inoperable is less severe than an unsafe operable vehicle. When assigning severity rating consideration should be given to the amount of experience and prior knowledge held by the student team. For this reason the assumption is made that there would be a greater number of high severity items than for a standard OEM.

3.5.7 Potential Cause/Mechanism of Failure

The potential cause of the failure for this DFMEA is defined as the root cause of the listed failure. The potential cause of the failure should be specific to the failure mode, not the cause of the listed effect. Normal failures include situations of: incorrect material specified, over-stressing, or improper connection procedures. The potential causes of mechanical system failures should be listed also as mechanical cause such as an improperly specified dimension. However with the controller requirements potential causes may be caused by improper control code or the physical assembly of the wire harness. For this reason, both physical and virtual causes are considered for the inverter subsystem.

3.5.8 Occurrence

The occurrence of the failure for this DFMEA is defined as the likelihood that the mechanism of failure or potential cause will occur. The occurrence scale show in Table 3-10 was used during DFMEA Motor Team meetings to rate the occurrence of every potential risk developed on a scale from one to ten.

Table 3-10: Occurrence Rankings adapted from Standard (2002)

Rating	Occurrence	
	Probability of Failure	**Criteria**
10	Very High: New technology/new design with no history	≥ 100 per thousand pieces >/= 1 in 10
9	High: Failure is inevitable with new design, new application, or change in duty cycle/operating conditions	50 per thousand pieces 1 in 20
8	High: Failure is likely with new design, new application, or change in duty cycle/operating conditions	20 per thousand pieces 1 in 50
7	High: Failure is uncertain with new design, new application, or change in duty cycle/operating conditions	10 per thousand pieces 1 in 100
6	Moderate: Frequent failures associated with similar designs or in design simulation and testing.	2 per thousand pieces 1 in 500
5	Moderate: Occasional failures associated with similar designs or in design simulation and testing.	.5 per thousand pieces 1 in 2,000
4	Moderate: Isolated failures associated with similar design or in design simulation and testing.	.1 per thousand pieces 1 in 10,000
3	Low: Only isolated failures associated with almost identical design or in design simulation and testing.	.01 per thousand pieces 1 in 100,000
2	Low: No observed failures associated with almost identical design or in design simulation and testing.	≤.001 per thousand pieces 1 in 1,000,000
1	Very Low: Failure is eliminated through preventative control	Failure is eliminated through preventative control

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From this scale, an occurrence rating of a one is assigned to any risk whose likelihood is deemed eliminated through the specified preventative measures. A rating of one is prescribed for a production part or system that is being implemented into the current design and the function being analyzed is handled by the supplier or manufacturer. An example of this would be the inverter for a motor system. The likelihood of improper control code on a production inverter is very low and not affected by team actions, therefore receives a ranking of one. An occurrence rating of two and three are given to any cause whose likelihood is considered relatively low for the team to undertake. An example of this is the monitoring of the temperature of the ESS. Redundancies within the thermal monitoring systems of the ESS and operational modes of the vehicle ensure that a maximum temperature is not surpassed and therefore can be deemed eliminated through current preventative measures. Increasing in occurrence are ratings of four, five, and six whose frequency increases and can be seen throughout similar designs or simulations. For any system, component, or function that has been tested in a previous manner the likelihood should not exceed six. An example of a rating between four and six is improper control code on the HVSC as there is experience working with similar controllers, but still a large learning curve and chance of faulty control code. For any completely new design an occurrence of seven is the least possible value as nothing has been previously done to state the rate of failure. Occurrence rankings of seven, eight, and nine are attributed to increasing the level of unknown for the areas of design, application, and operating conditions. Finally, a cause is only deemed very high if the design, application, and operating conditions are all completely new and have no prior testing in any other setting. An example of a ranking between seven and nine is a spline specification for a differential input spline that is reproduced for a custom motor shaft. This spline has been used in similar applications, but the new operating conditions raise the likelihood of the specified cause occurring. An occurrence of 10 is unlikely for any HEVT system or component as there are various examples that are available of numerous systems that were tested and implemented into past competition vehicles. However, in the event that the competition were to embark on a new technology that HEVT has no prior knowledge of or related experience with – a ranking of 10 would be expected. For any production part that is modified from the original design, application, or operating conditions the FMEA team will evaluate the likelihood of failure based upon team experience with the part and reach a consensus on the rating.

3.5.9 Current Design Controls – Prevention Method

The prevention method of the failure for this DFMEA is defined as the methods that are being enacted by the team to reduce how often the failure occurs. For this analysis, the prevention methods were limited to those that the team would be able to develop and implement. If a preventative measure is capable by a supplier or manufacturer for a given component, the appropriate ranking for the DFMEA will reflect that the team sees no preventative measure that the team can act on to prevent the failure from occurring.

3.5.10 Current Design Controls – Detection Method

The detection method of the failure for this DFMEA is defined as the methods that can be implemented by the team to detect when a failure occurs. For this analysis the detection methods were limited to those that team would be able to develop and implement. If a detection method is solely able to be applied by the component supplier or manufacturer, but not reproducible by the team, the appropriate ranking for the DFMEA will reflect that the team has no detection methods in place for a given failure.

3.5.11 Detection

The detection rating shows a significant difference for mechanical and the controller analysis within the same DFMEA document. For mechanical risks the detection is defined as the ability of the current design controls to detect the cause of the failure. While for controller risks the detection is defined as the ability of the current design controls to detect the failure mode as a whole. This difference is due to the fact that for the cause of controller risks are attributed to mechanical issues but the detection method for controller risks are tied directly to the HVSC or the inverter receiving/not receiving an expected signal. This difference allows for a more accurate representation of a team's ability to detect the actual fault as opposed to concerning themselves with the cause of the fault which may be more influential from a control code. The detection scale show in Table 3-11 was used during DFMEA Motor Team meetings to rate the ability to detect every potential risk developed on a scale from one to ten. Unlike severity and occurrence a detection level of 10 means that there is no current design control in place to detect the failure or cause.

Table 3-11: Detection Rankings adapted from Standard (2002)

Rating	Detection		
	Detection	**Criteria: Controller**	**Criteria: Mechanical**
10	Absolute Uncertainty	Cannot Detect	No current design control; Cannot detect or is not analyzed
9	Difficult to Detect	N/A	Design analysis/detection controls have a weak detection capability; Virtual Analysis (e.g. CAE, FEA, etc.) is not correlated to expected/actual operating conditions.
8	Post Design Freeze and Prior to Launch	In Vehicle Testing, not probable/possible to simulate fault	Product verification/validation after design freeze and prior to launch with pass/fail testing (Sub-system or system testing with acceptance criteria e.g. Ride & handling, shipping evaluation, etc.)
7	Post Design Freeze and Prior to Launch	N/A	Product verification/validation after design freeze and prior to launch with test to failure testing (Sub-system or system testing until failure occurs, testing of system interactions, etc.)
6	Post Design Freeze and Prior to Launch	Test and Validate in HIL, not possible to set in SIL	Product verification/validation after design freeze and prior to launch with degradation testing (Sub-system or system testing after durability test e.g. Function check)
5	Prior to Design Freeze	N/A	Product validation (reliability testing, development or validation tests) prior to design freeze using pass/fail testing
4	Prior to Design Freeze	Test and Validate in SIL	Product validation (reliability testing, development or validation tests) prior to design freeze using test to failure (e.g. until leaks, yields, cracks, etc.)
3	Prior to Design Freeze	N/A	Product validation (reliability testing, development or validation tests) prior to design freeze using degradation testing (e.g. data trends, before/after values, etc.)
2	Virtual Analysis - Correlated	Test and Validate in MIL - Design Flaw of functionality. Directly impacts results of model	Design analysis/detection controls have a strong detection capability. Virtual Analysis (e.g. CAE, FEA, etc.) Is highly correlated with actual and/or expected operating conditions prior to design freeze.
1	Detection not applicable; Failure Prevention	Detection not applicable; Failure Prevention	Failure cause or failure mode cannot occur because it is fully prevented through design solutions (e.g. Proven design standard/best practice or common material, etc.)

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The detection scale varies from the severity and occurrence in that there is a separate criteria for which the controller risks should be evaluated upon versus mechanical components. In order to properly compare mechanical and controller detection the proper stages of detection for controller development were identified. The six possible ranks for a controller detection were developed as: Failure prevention, MIL Testing, SIL Testing and Validation, HIL Testing and Validation, In Vehicle Testing, and finally unable to detect the risk. A detection rating of “one” is consistent between mechanical and controller components and means the failure cause or mode is entirely prevented with the current design controls set in place by the team. As with severity and occurrence, the detection is the ability of the team, not an outside party, to detect the risks. For a controller risk to receive a detection rating of “two” the failure must be able to test within MIL, the earliest design phase for the controller and allows system flaws with interactions to be exposed. A mechanical criteria of a detection value of two is associated with those risks that are able to be detected early with FEA or another similar method of analysis for mechanical systems. The amount of time spent in development towards full vehicle integration and functionality increases as the ability to detect the failures or causes becomes more difficult for both the controller and mechanical systems.

3.5.12 Risk Priority Number, Criticality Number, and Thresholds

The risk priority number for a given potential failure is the product of the severity (S), occurrence (O), and detection (D) values.

$$S * O * D = RPN \qquad \textbf{Equation 1}$$

The RPN is the end result of an effective DFMEA that allows for the entire team to understand the relative risk of potential failures within a given system. Any determined RPN for an analyzed system is relative to the specific application and approach in development and design (Standard 2002). Due to the relative nature of an RPN setting a constant threshold to be applied to all designs and systems is not universally recommended. Table 3-12 shows two potential motor risks with varying RPNs and their respective S, O, and D values.

Table 3-12: Example Resultant RPNs for varying potential risks

Potential Failure	Severity	Occurrence	Detection	RPN
Potential Failure A	9	10	2	180
Potential Failure B	8	5	10	400

If a threshold value were set of 200, the necessary mitigation strategy would only require that the potential failure B be addressed. Potential failure A has a higher severity than the potential failure B but by the threshold would not need to be analyzed further. Establishing thresholds may result in team members attempting to rationalize assigning lower detection or occurrence values to reduce the overall RPN of a potential failure.

One method that is suggested as a means to elevate focusing solely on an RPN threshold is to analyze the Criticality Number of a potential risk. The criticality number, SO, is the product of the severity and the occurrence as show in equation 2.

$$S * O = Criticality\ Number = SO \qquad \textbf{Equation 2}$$

Looking again at the example from Table 3-12, if a SO threshold of 50 was set, potential failure A would be analyzed but not potential failure B. Focusing on the criticality number allows the team to emphasize the reduction in the occurrence of a potential failure mode, which in turn would reduce the overall RPN as well.

A combination of analysis of both RPN and SO thresholds is suggested for the team to begin addressing the high risk failure modes. For a given DFMEA, the thresholds should not be set until the genesis of the original DFMEA or SFMEA is complete. There is no universally applied threshold for RPN or SO that would be both beneficial and representative of the most important risks to address for the multiple subsystems of a hybrid vehicle.

3.5.13 Recommended Actions

Actions must be assigned to each RPN and SO over the predetermined threshold for the system after the initial RPNs and SOs have been developed and analyzed. The purpose of the recommendation actions are to mitigate the risk of the severity of a potential failure mode (Standard 2002). The inherent severity for given failure mode is not subject to change by the nature of the ranking system and can only be brought down by a design or process change. Therefore the recommendation actions look at reducing the Occurrence and Detection values for the specific failure mode to lower the overall RPN or SO. The actions should aim to improve the overall design and increase the customer satisfaction. Recommended actions should be completed as the FMEA team progresses through the top priority risks and there may be potential failure modes with no recommendation actions available or known for the current design.

Accompanying the recommended actions should be the responsible engineer, required completion date, and the actual actions taken by the engineer to reduce the RPN or SO. All of this information should be stored on the master DFMEA sheet. The final information required for the recommended actions are the revised ratings for Severity, Detection, and Occurrence. The resultant new RPN and SO should be compared to the previous values to determine if further actions is required to bring the risk to acceptable levels determined by the team. The acceptable level for revised ratings should not be held to the original thresholds set for RPN or SO as the potential failure originally was of concern in the design and a new level should be discussed with the entire FMEA team to determine if the recommended actions suffice. If after the recommended actions are taken and the potential failure mode does not have a RPN or SO low enough to be agreed upon by the members of the FMEA Team, a decision must whether additional actions should be taken or if the revised ratings are the most that can be done to lower the risk of the failure mode. The decision of continuing of refining the design to lower the RPNs must be balanced with the additional time and costs developed through the refinement. Teams must establish milestones and timelines that guide the designs and ensure product delivery and functions within the vehicle development process.

4 Model Application

After providing complete definitions for the DFMEA Model, this thesis will now detail the analysis of the P3 motor system used by HEVT in EcoCAR 3. The developed FMEA Team with roles and responsibilities and record of meetings are shown to emphasize the importance of FMEA as a team endeavor, and how DFMEA must be a living document to provide accurate results. Once explained, the specific customers for the motor system DFMEA are examined to show the importance of customer requirement definition early on in the process. The system definitions, subsystems, and parts and interfaces are all be examined for the motor system – systematically going through the proper steps to complete a DFMEA. The motor component interfaces and block diagram will then be provided to show the interconnectedness of the system and the genesis of the motor function identification. One specific failure mode of the motor shaft spline connection is analyzed and the severity, potential cause, occurrence, current design controls, and detection methods are analyzed for the specific failure mode. Upon calculation of all motor system RPNs and SOs, a motor system specific RPN and SO thresholds is analyzed. Finally, the recommended actions that are taken for the motor shaft failure mode and the resultant revised rankings are assessed. While one potential failure mode is analyzed in detail for this thesis, similar analysis are done for all failure modes whose RPN or SO were above the determined thresholds. Throughout this section CAD has not been shown due to the proprietary nature of the Camaro by General Motors. Figure 4-1 shows a CAD rendering of the complete P3 Motor.

Figure 4-1: CAD of Custom P3 Motor

4.1 Motor Team Roles and Responsibilities

Late in the first year of the competition, the FMEA team for the motor system was formed as the early stages of the design process began. There is no high level SFMEA performed on the motor system due to timing of the design of the motor and the development of VTS. Table 4-1 gives a complete list of individuals who have worked as a part of the motor system FMEA.

Table 4-1:Motor System FMEA Team Member and responsibilities

Name	Organization	Responsibility/Role
Lucas Shoults	HEVT	Motor System FMEA Lead Engineer
Peter Bedrosian	HEVT	Designer – Motor Housing and Motor shaft
Matt Moniot	HEVT	Designer – Motor End Bells and Terminal Box
Devon Tanner	HEVT	Designer - Bearings
Daniel Chadwick	HEVT	Designer – Motor Mounting Structures
Quinn Roels	HEVT	Designer – Drawings for Manufacture
Ryan Barrett	HEVT	Validation – FEA
Samuel Reinsel	HEVT	Validation – Control Code Testing
Chris Flake	HEVT	Validation – Control Code Testing
Jack Stevenson	HEVT	Validation – Interface Engineer
Jake Mathey	HEVT	Validation – Interface Engineer
Alex Neblett	HEVT	Systems Safety Manager
Doug Nelson	HEVT	Lead Faculty Advisor
Ethan Phillip	InMotion US	Supplier Representative – Mechanical Design
Brad Monday	InMotion US	Supplier Representative – Electromagnetics
Ian Hovey	InMotion US	Supplier Representative – Mechanical Design
Cameron Forbes	InMotion US	Supplier Representative – Mechanical Design
David Coulson	InMotion US	Supplier Representative – Electromagnetics
David Pape	InMotion US	Supplier Representative – Validation and Testing

Table 4-1 shows how over the entire design of the motor, 19 individuals were required at one point or another for their insight and input on the motor system DFMEA. Simpler systems of the vehicle may not require as extensive as a list, but the FMEA engineer should not assume that a small team of four will be able to cover all aspects of a system.

4.2 Motor System Customer Requirements

Before any DFMEA is conducted on the motor system the FMEA Team must define the customer and customer requirements for all customers involved in the design. As described in section 3.3 the four customers to consider are the end user, governing organizations, supplier, and internal customers.

4.2.1 End User and Governing Organizations Requirements

For the motor system and for all component systems within the vehicle for EcoCAR 3, the end user was defined in the Consumer Market Research Report as the FTP. The FTP desires for a famous American brand name, exciting ride, and fuel savings are all metrics and considerations that must be taken into account when designing the vehicle as a whole. Due to the large influence of the P3 motor system in vehicle operation, the motor system is designed with all of these aspects in mind so that the consumer is delighted, not just satisfied, from the driver experience, perceived political image, and cost savings (HEVT 2014). The end user desires and requirements are distilled down through a vehicle bench marking exercise which included a 2015 V6 Chevrolet Camaro, 2015 V8 Chevrolet

Camaro, 2015 V6 Ford Mustang, and a 2015 V6 Dodge Challenger to determine the appropriate team VTS to meet the FTP customer needs.

Similar to the end user requirements for the motor system are governing organization requirements. These requirements set in place by ANL and GM specify desired vehicle criteria. In addition to the vehicle performance specifications, there are the NYSR which require specific structural analysis to be performed for modifications to select areas of the vehicle, No Cut Zones (NCZs) (ANL 2016). The quantifiable requirements for the governing organizations are the competition required and target VTS from Table 1-2. Similarly, the quantifiable requirements for the end user are the HEVT Target VTS from Table 1-2.

The NCZs are predefined structural members of the vehicle that are not permitted to be modified by the team without the submission of a structural waiver. The structural requirements have teams perform a successful comparative stress analysis using finite element analysis (FEA) to prove the integrity of the proposed modification over the entire rear structure of the vehicle. The boundary conditions and portion of the vehicle structure to be analyzed are provided by GM. The modifications are incorporated into the stock vehicle structure and the identical boundary constraints and load cases are applied. The developed stresses in the modified structure is then compared to a table of allowable stresses provided by GM. These restrictions on body modifications and passenger capacity placed requirements of physical motor size, placement, and as a result the motor performance technical specifications. Figures detailing the NCZs can be found in the proprietary NYSR (ANL 2016). Any vehicle body structure in red is restricted from any structural modification, yellow is permitted with the approval of a structural waiver, and the green structures can be removed without any notice to the competition organizers. From a packaging study conducted, the envelope available to package the motor is an outer diameter of 300 mm by an overall motor length of 300 mm.

Only focusing on the governing organization requirements would not ensure that the end user desires for the product are met. Both the governing requirements and end user desires were balanced with the motor system to ensure both were satisfied with the final design. The motor system is one of two torque producing components within the vehicle, so all performance, economy, and even spatial requirements are affected by the design and implementation of the motor.

During the powertrain selection, the motor was sized to allow the vehicle to complete the EcoCAR 3 4-cycle drive schedule while operating solely in CD. The EcoCAR 3 4-cycle drive schedule is a combination the 505, Highway Fuel Economy Test (HwFET), US06 City, and US06 Highway drive cycles with the respective weightings and characteristics shown in Table 4-2.

The weighting of the four drives schedules makes up the Emissions and Energy Consumption (E&EC) during the third and fourth year of competition that is the single largest pointed dynamic event in the competition. Meeting the US06 city accelerations without any assist from the engine requires a motor peak output torque of 640 Nm operating at a base speed of 1500 RPM.

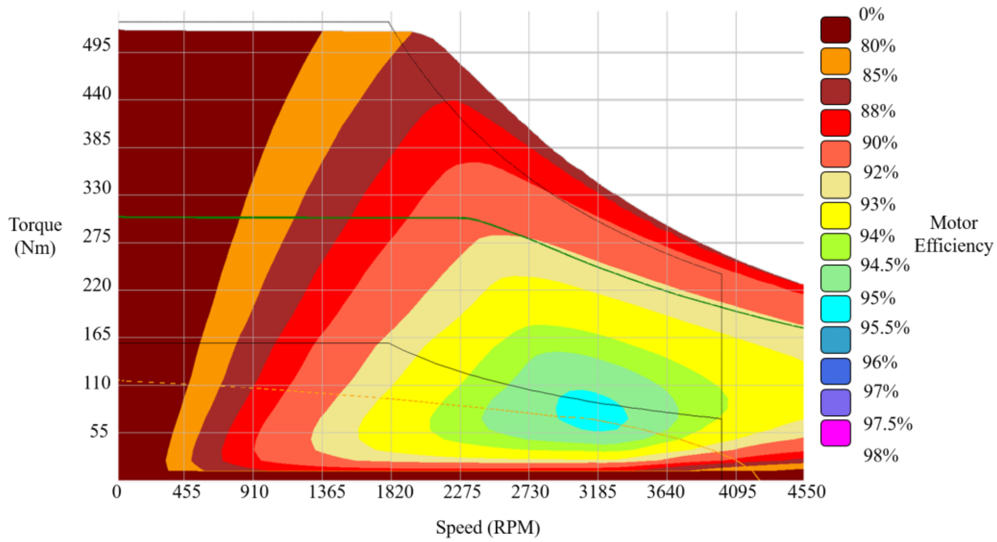
Table 4-2: EcoCAR 3 4-Cycle Weighting (Adapted from Argonne NYSR, used in Fair Use 2016)

Drive Cycle	Characteristics	Average Speed	Average Acceleration	Weighting Factor for EcoCAR 3 Drive Cycle
		mph	m/s^2	%
505	Low Speed	25.5	0.51	29
HWFET	Mid Speed	48.3	0.19	12
US06 City	Low Speed, Aggressive	27.5	1.29	14
US06 Highway	High Speed, Aggressive	61.2	0.34	45

4.2.2 Supplier Requirements

HEVT worked with local motor designer and manufacturer InMotion throughout the entire development process for the motor system. InMotion assumes the role as a customer with the restraints and requirements from the design. Early on in the design of the motor system the peak and continuous torque, and base and max speed of the motor were needed for the electromagnetic design to begin. As previously stated HEVT desired a peak torque of 640 Nm at a base speed of 1500 RPM. Torque is the product of force applied over a given radius, an increase in the overall radius of a radial motor results in a linear increase in the circumference where the stator pole shoes are located (Petro 2011). This increase in circumference leads to a linear increase in the flux carrying area of the pole shoes. As a result of the linear increase of the flux area and radius, the torque of the motor increases with the square of the diameter (Petro 2011). Due to the torque-diameter relation, the desired specifications of 640 Nm at 1500 RPM required a larger diameter motor than the team was able to package within the allocated 300 mm outer diameter by 300 mm length while complying with the requirements of the FTP or ANL for passenger seating and adhering to NCZs.

The motor FMEA team worked with team designers and InMotion to reduce the size and maximum output torque of the motor to 500 Nm to ensure that the motor would be properly packaged within the vehicle and adhere to all customer requirements. The increase in base speed of the motor from 1500 RPM to 1900 RPM provides the original motor peak output power of 100 kW. The reduction in maximum torque impacts the low end accelerations leading to increased percentage of trace misses on the US06 City drive cycle, but was a necessary tradeoff to meet governing organization requirements of packaging. Figure 4-2 shows the simulated torque verses speed plot for the 500 Nm, 1900 RPM motor with motor and inverter operating efficiency.



Used in Fair Use 2016

Figure 4-2: Simulated Motor Torque vs Motor Speed (InMotion 2015)

From Figure 4-2, the motor achieves maximum torque of roughly 500 Nm up to the selected base speed of 1900 RPM where the torque beings to decrease with increasing speed along the constant power line of the motor. Optimum motor system efficiency is achieved when the motor is operating closer to the higher operating speeds and lower torque.

4.2.3 Internal Customer Requirements

The final customer for the motor system are the various component systems within the HEVT Camaro that interact with the motor system, directly or indirectly, and the various individual requirements for parts within the motor system itself. In order to establish these customers' requirements, a vehicle level block diagram was developed to show the interconnectedness between the various component systems. The internal customer requirements should be developed in a SFMEA. The connections that are considered for vehicle level interactions with the motor system are shown in Figure 4-3.

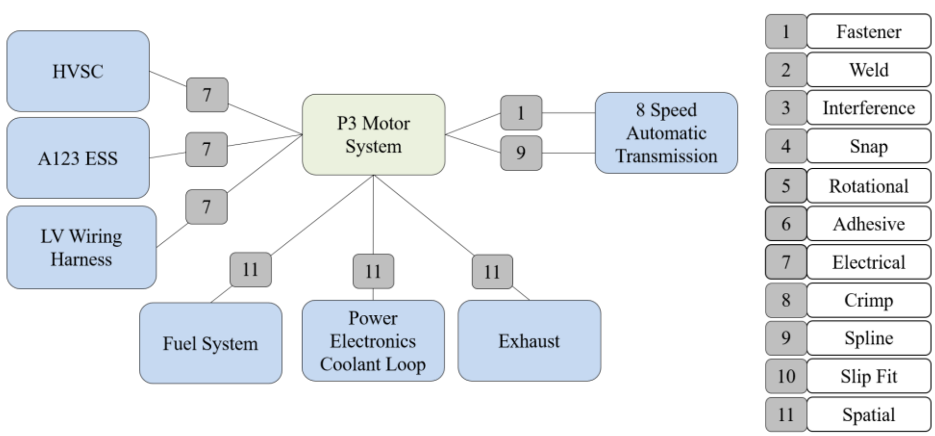


Figure 4-3: Block Diagram of P3 Motor System Vehicle Level Connections

Only direct connections to the motor system were listed and considered. The author notes that the motor system and engine interact to provide torque together when operating in CS.

However, for the purpose of DFMEA this connection is indirectly through the eight-speed automatic transmission and therefore negated. For the analysis of driveline connections, from the output of the transmission to the connection to the motor shaft the drive shaft was divided between the transmission component system and the motor system. All connections post transmission output and before and including the center bearing in the vehicle were considered to be part of the transmission system. Figure 4-4 shows a graphical representation of the powertrain to convey component placement.

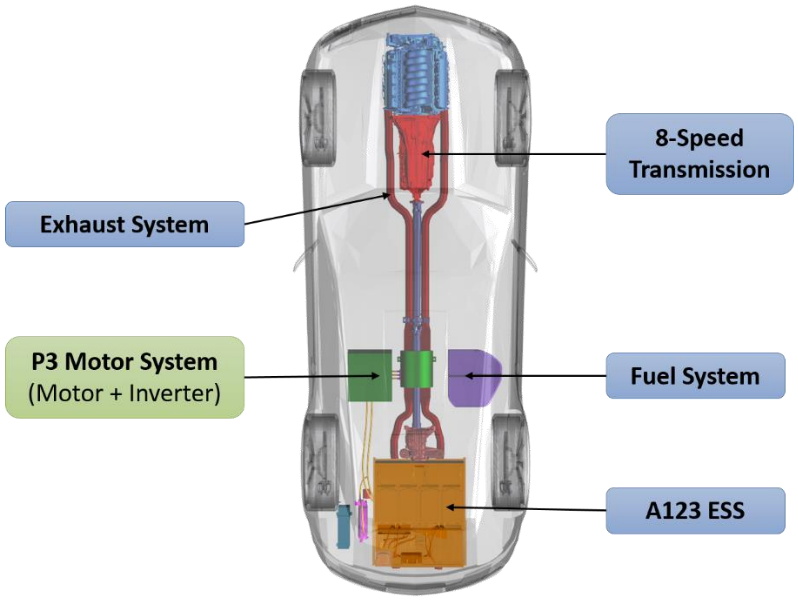


Figure 4-4: CAD of components locations relevant to Motor System

All connections after the center bearing to the input of the rear differential are considered in the DFMEA analysis for the motor system. The HVSC, ESS, and LV wiring harness are all electrically connected to the motor system and have internal requirements to be met. All of these internal component requirements between systems are more appropriate addressed in a SFMEA. However the author felt it is important to entirely describe the customer for a given component system. The spatial connection represented by "11" does not represent a physical connection between the systems, but that the design and integration of the fuel system, power electronics coolant loop, and exhaust system are all directly impacted by the final design specifications of the motor system – specifically in the size and placement of the motor system. The seven component systems that are directly connected to the packaging of the motor system represent the internal customers external to the system being analyzed. Finally, the internal customer that will be analyzed with a DFMEA are the individual parts and interfaces within the motor system itself. In order to properly encapsulate the interactions and interfaces with the motor, InMotion was involved in the early stages of the DFMEA to ensure no components were missed in the development. The in-depth analysis of the internal motor system requirements and interfaces are presented in Section 4.4.2 in order to follow the outlined DFMEA procedure. Table 4-3 provides a summary of the customer for the motor system DMFEA and their respective requirements.

Table 4-3: Summary of Motor System Customers and Requirements

Customer Level	Customer	Requirements/Specifications
End User	Forward Thinking Patriot	CMRR and Team Target VTS
Governing Organization	Argonne National Labs and General Motors	NYSR, NCZs, and competition required/suggested VTS
Supplier	InMotion	Motor and inverter limitations within design constraints of HEVT – Size, Torque Output, Speed, Current & Voltage
Internal – Vehicle System	HVSC	SFMEA conducted to develop component system requirements
	ESS	
	LV Wiring Harness	
	8-Speed Transmission	
	Fuel System	
	Exhaust System	
	Power Electronics Coolant Loop	
Internal – Motor System	Internal Connections within Motor System	Appendix A. Functional and Design Requirements

4.3 FMEA Naming and Numbering

The motor system DFMEA followed the prescribed guidelines in section 3.3 for developing a FMEA name and number with the results presented in Table 4-4.

Table 4-4: FMEA Name and Number Convention for Motor System

FMEA Name	EcoCAR 3 P3 Motor System
FMEA No.	D_EC3_2_2015-11-22-1413_17_LWS

Table 4-5 shows user inputs that result in the above FMEA number for which all systems and components within the vehicle are able to be sorted.

Table 4-5: FMEA Name and Numbering Convention for Motor System

FMEA Type	Design
Competition	EcoCAR 3
Component System	Electric Motor Systems
Creation Date (YYYY-MM-DD-TTTT)	2015-11-22-1413
Revision	17
Author (Initials)	LWS

This naming and numbering is used throughout the DFMEA process to properly track changes and remain consistent in explanations between FMEA Team members working on the motor system. The same thirteen vehicle level systems are maintained and the motor system falls under electric motor systems.

4.4 Motor System DFMEA Columns

The core of the motor DFMEA is contained within the 13 areas described within section 3.4 and are represented on the master DFMEA worksheet as columns. This section will progress through each of the columns represented providing all subsystems, parts and interfaces, describing the process by which functions are selected and a summary of possible functions for the motor system before focusing in on the highest RPN developed through the DFMEA of the motor shaft spline connection. For the remaining column descriptions, the motor shaft spline connection and highest RPN controller failure mode for the inverter failing to send a PDO timeout message are analyzed in detail to provide an example of the analysis performed on all line items. The various recommended actions taken on the motor shaft spline connection will be discussed and their revised RPNs shown.

4.4.1 Motor System Subsystems Identification

The subsystems for the motor system DFMEA is one area where there are significant differences between the mechanical components and a controller requirement. For this thesis analyzing the motor system, Table 4-6 shows the entire list of subsystems considered during the motor system DFMEA.

Table 4-6: Subsystem Categories

Subsystem	Mechanical or Controller
Inverter	Controller
Motor Assembly	Mechanical
Motor Mount	
Motor Wires	
Motor Shaft	
Resolver	
Rotor	
Stator	

The inverter is the only subsystem classified as controller due to the analysis being confined to the communication between the motor and the inverter, and the inverter and the hybrid vehicle supervisor controller (HVSC). The remaining subsystems were generated with the help of the motor manufacturer to encompass the remaining areas of the motor system that should be included in this analysis. The subsystem level is analyzed first to break down the entire system selected into which parts are to be analyzed – ensuring nothing is overlooked. Figure 4-5 shows a CAD rendering of the motor system as a cross-section with select callouts established during the motor system DFMEA.

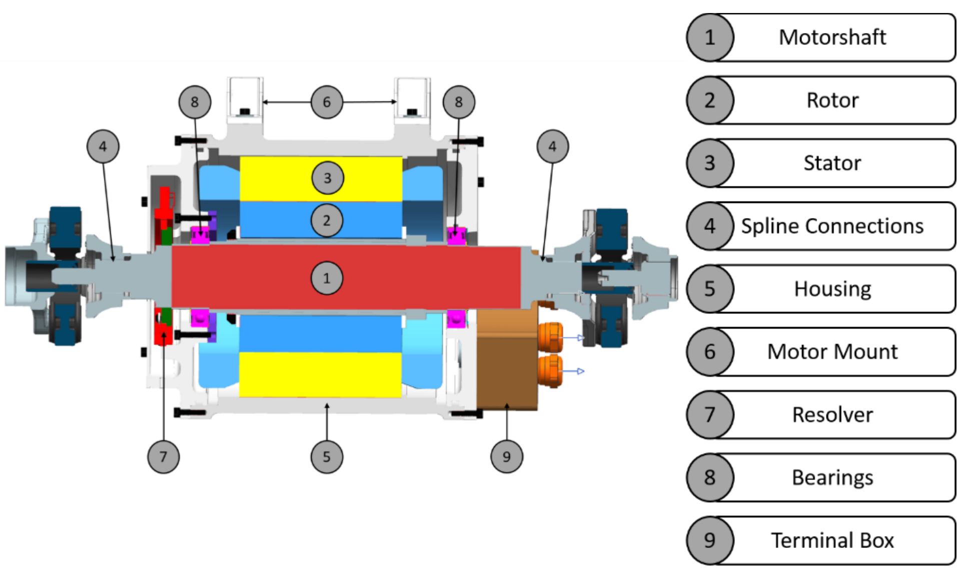


Figure 4-5: CAD Cross-section of Motor

4.4.2 Motor System Parts and Interfaces

4.4.2.1 Motor System Parts and Interfaces Connections

After having established an agreed upon subsystem list, the individual parts and interface connections are developed with the entire FMEA team and relevant suppliers if available. For the motor system, the parts and interfaces are developed in a meeting with InMotion and verified with the entire motor FMEA team. Table 4-7 shows the subsystems with respective parts and interfaces for both mechanical subsystems and the inverter. For this analysis the temperature sensors are considered part of the LV harness.

Table 4-7: Motor Subsystems and respective parts/interfaces

Mechanical Subsystems		**Controller Subsystems**	
Subsystem	Part/Interface	Subsystem	Part/Interface
Motor Assembly	Bearings	Inverter	Communication Input
	Bearing Clamps		Communication Output
	Terminal Box		Constraint
	Terminal Box Lid		Emergency Response
	End Bells		Start Up
	Housing		I/O Pins 1 – 39
Motor Mount	Floor pan		3 Phase Lines
	Motor Mounts		HV DC Lines
Motor Cables	3-phase lines		
	LV harness		
Motor Shaft	Motor shaft		
	Resolver Stator		
Resolver	Resolver Rotor		
	Resolver Clamp		
	Resolver Adapter		
Rotor	Rotor Core		
	Rotor Laminations		
Stator	Stator Lamination		
	Stator Windings		

From the parts and interfaces in Table 4-7 the connection types presented in section 4.2 are modified to represent the connections between all mechanical subsystems. This decomposition is not performed for the controller subsystems as all inverter connections are communication and not physical connections. Table 4-8 and Table 4-9 show the developed connection types and connection matrix for the motor system. Table 4-9 was truncated by removing columns with no component connections.

Table 4-8: Types of Motor System Mechanical Connections

#	**Type**
1	Fastener
2	Weld
3	Interference Fit
4	Snap Fit
5	Rotational
6	Adhesive
7	Electrical (Pinned/Bolted)
8	Crimp
9	Spline
10	Slip Fit

Table 4-9: Mechanical Motor Interface Connections Matrix

Components	Bearings	Bearing Clamps	Terminal Box	Terminal Box Lid	End Bells	Housing	Floor pan	3-phase lines	LV harness	Shaft	Resolver Stator	Resolver Rotor	Rotor Core	Stator Lamination
Bearings														
Bearing Clamps	1	x												
Terminal Box	0	0	x											
Terminal Box Lid	0	0	1	x										
End Bells	5,10	1	0	1	x									
Housing	0	0	0	0	1	x								
Floor pan	0	0	0	0	0	0	x							
Motor Mounts	0	0	0	0	0	1	1	0						
3-phase lines	0	0	1,7,8	1	0	0	0	x						
LV harness	0	0	0	0	7,8	0	0	0	x					
Shaft	3	0	0	0	0	0	0	0	0	x				
Resolver Stator	0	0	0	0	0	0	0	0	7,8	0	x			
Resolver Rotor	0	0	0	0	0	0	0	0	0	0	0	x		
Resolver Clamp	0	0	0	0	1	0	0	0	0	0	1	0		
Resolver Adapter	0	0	0	0	0	0	0	0	0	3	0	3		
Rotor Core	0	0	0	0	0	0	0	0	0	0	0	0	x	
Rotor Laminations	0	0	0	0	0	0	0	0	0	6,10	0	0	6,10	
Stator Lamination	0	0	0	0	0	3	0	0	0	0	0	0	0	x
Stator Windings	0	0	0	0	0	0	0	7	7,8	0	0	0	0	6

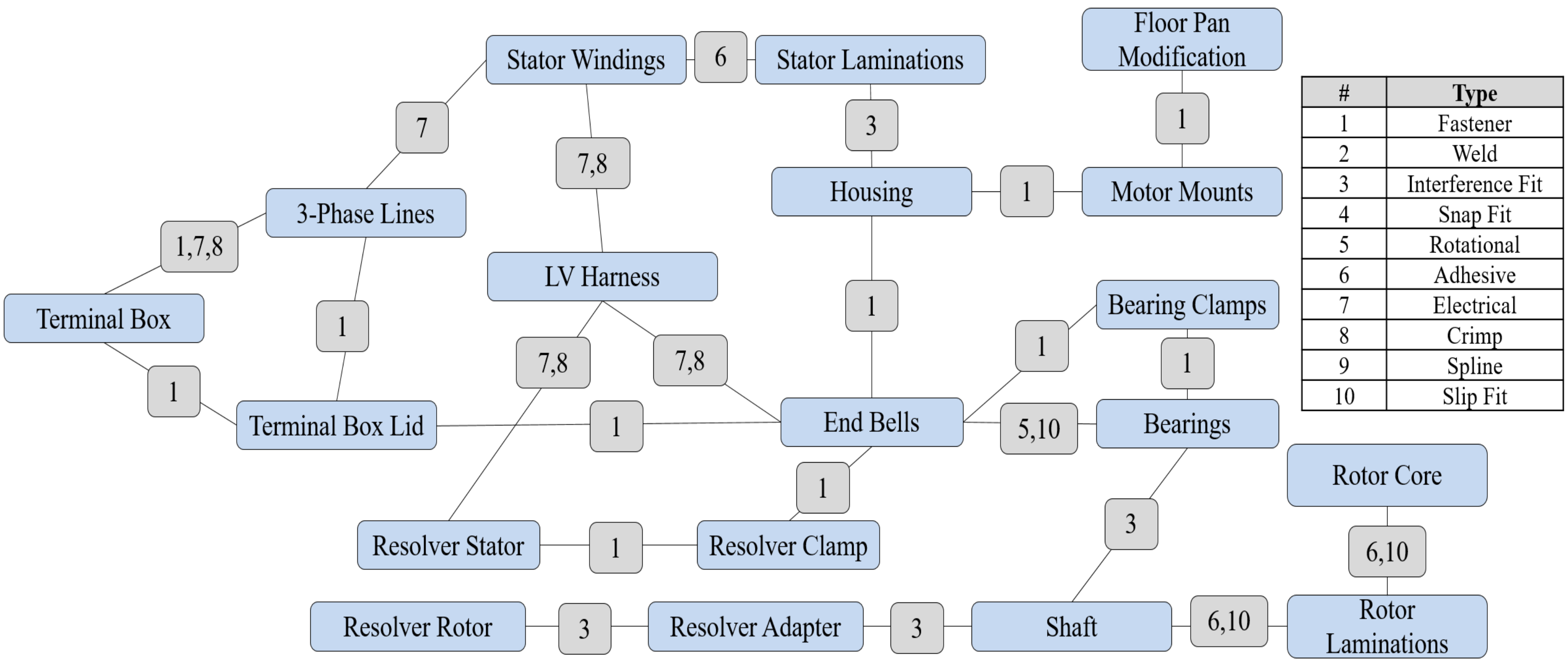
Shown in Table 4-10 is the I/O pin descriptions for the inverter to HVSC connector with the specific pin function. Each one of these pins is evaluated under three failure modes: short to ground, short to open, and short to logic. For the complete effects for these failures refer to Appendix B for the complete motor system DFMEA.

4.4.2.2 Motor System Block Diagram Generation

Table 4-10: Inverter ACH 6530 I/O Pin Descriptions (InMotion 2016)

Pin	Type	Name	Description
1	Input	Motor Temperature Sensor 2	Isolated Motor Temperature Sensor Input
2	Input	Motor Temperature Sensor 1 GND	Isolated Motor Temperature Ground
3	Input	Motor Temperature Sensor 1	Isolated Motor Temperature Sensor Input
4	Input	Motor Temperature Sensor 2 GND	Isolated Motor Temperature Ground
5	Output	Chassis	For terminate cable shield
6	Output	Resolver Excitation +	Excitation Output for Resolver
7	Input	Resolver COS+	Input resolver COS
8	Input	Resolver COS-	Input resolver COS
9	Output	Resolver Excitation -	Excitation Output for Resolver
10	Input	Resolver SIN+	Input resolver SIN
11	Input	Resolver SIN-	Input resolver SIN
12	Input	DIGITAL INPUT GND	
13	Input	DIGITAL INPUT 4	Digital Input with internal pull-up resistor
14	Input	DIGITAL INPUT 3	Digital Input with internal pull-up resistor
15	Input	DIGITAL INPUT 2	Digital Input with internal pull-up resistor
16	Input	DIGITAL INPUT GND	
17	Input	DIGITAL INPUT GND	
18	Input	Analog Input	Analog Input
19	Output	HVIL_OUT	Hazardous Voltage Interlock Current Loop output
20	Input	HVIL_IN	Hazardous Voltage Interlock Current Loop input
21	Input	Analog Input	internal connection at pin 18
22	Input	J1939 CAN_H in	
23	Output	J1939 CAN_H out	internal connection at Pin 22
24	Input	J1939 CAN_H backup	
25	Input	J1939 CAN_L in	
26	Output	J1939 CAN_120R	Shall be external connection to Pin 23 for using Internal 120R
27	Input	J1939 CAN_L back up	
28	Input	Digital Input 1	
29	Input	CANopen CAN_L	
30	Input	CANopen CAN_H	
31	Input	Digital Input GND	
32	Input	STO_IN_2	Safe Torque Off, Digital Input with internal pull down resistor
33	Input	STO_IN_1	Safe Torque Off, Digital Input with internal pull down resistor
34	Output	High side out GND	For external load connect to high side out
35	Input	Unit_Enable	Digital input signal to HW enable the Unit. The signal controls the state of the logic power supply on or off, with internal pull down resistor
36	Input	Logic Supply	Logic supply input, the input voltage for the internal DC/DC and logic power supply
37	Output	High side out	On/Off MOSFET from logic supply for external load (relay)
38	Input	Logic_Supply GND	
39	Input	Logic_Supply	Internal Connection at Pin 36

Through using Table 4-9, the FMEA team is able to develop a component level block diagram for the motor system. Organization of the block diagram becomes ever more important as the complexity of the system and number of components increase. The motor system block diagram is provided in Figure 4-6 for the component interfaces developed in Table 4-9.



#	Type
1	Fastener
2	Weld
3	Interference Fit
4	Snap Fit
5	Rotational
6	Adhesive
7	Electrical
8	Crimp
9	Spline
10	Slip Fit

Figure 4-6: Block Diagram for Motor System Component Interfaces

4.4.3 Motor System Design Functions

The design functions for the motor DFMEA are generated internally with the motor team and aimed to meet the all levels of customer requirements. These functions are developed by evaluating the block diagram and connections, as well as the overall subsystem functions known by the FMEA team from prior motor experience. The functional requirements and design constraints of the mechanical motor system can be found in Appendix A. For the remainder of the analysis the highest risk item for the mechanical and inverter system will be discussed. The complete motor DFMEA can be found in Appendix B. Table 4-11 shows the selected highest RPN mechanical system and inverter system risk items.

Table 4-11: Design Functions of most critical RPNs for Motor System

Subsystem	Part/Interface	Design Function
Motor shaft	Spline Connections	Provide concentric connection and desired torque transmission between center bearing and rear differential
Inverter	Communication Input	The Inverter shall send a PDO timeout message

Analyzing the function of the motor shaft was performed by the team to encapsulate two important traits of the motor shaft of providing concentric connection and desired torque transmission between center bearing and rear differential. The connections can be considered two individual design functions in their own right, however the motor FMEA team concluded that the providing the concentric connection and transmitting the desired torque are two closely related and interdependent upon one another to be properly analyzed individually in the DFMEA. For the proper functionality of the vehicle and customer requirements to be met, the spline connection must be both concentric and rated to transmit the required torque for the system. The torque rating is derived from shock loads, anti-locking braking system incidents, and sudden accelerations that placed large torques on the driveline components. GKN driveline designs suggest shock loads are roughly twice as large as the maximum vehicle output torque.

Secondly, the inverter design function of sending a PDO timeout message. There are two types of CANopen controller protocols: Network management (NMT) protocols and heartbeat protocols. In a heartbeat protocol, each controller on a network broadcasts a heartbeat signal over CAN to confirm that the controller is still active. NMT protocols use a single master controller that activates all others through a message over CAN. Rather than each controller having individual heartbeat signal, each controller on the BUS has a set of cyclical messages known as process data objects (PDOs). Each component has specific cyclical transmitted and received PDOs, which are used in place of the heartbeat to determine component functionality. PDOs also contain the information that the master and slave controller need to use on a regular basis, such as torque command, bus voltage, and command mode.

The inverter uses the received PDOs to determine if the CAN bus is functioning properly. When a PDO from the master controller (the HVSC) is not received for a full second, the inverter will send a PDO timeout and cease function. The inverter must be commanded to shut down and restart through normal procedures. This behavior ensures that the inverter does not continue to operate when the HVSC has possibly failed or lost power.

4.4.4 Motor System Potential Failure Modes

The potential failure modes for the motor DFMEA are generated internally with the motor team by evaluating the block diagram and connections, as well as the overall subsystem failure modes known by the FMEA team from prior motor experience. Table 4-12 presents the selected highest RPN mechanical and inverter system risk items with potential failure modes.

Table 4-12: Potential Failure Modes of most critical RPNs for Motor System

Subsystem	Part/Interface	Design Function	Potential Failure Mode
Motor shaft	Spline Connections	Provide concentric connection and desired torque transmission between center bearing and rear differential	Non-concentric connection fails to transmit driver demanded torque
Inverter	Communication Input	The Inverter shall send a PDO timeout message	The inverter does not send PDO timeout message when appropriate

The failure mode of the motor shaft is simply stated as failing to perform the desired design function of providing concentric connection and desired torque transmission between center bearing and rear differential. For DFMEA of the potential failure mode is more easily assessed when stated as a direct failure of the design function. This allows for greater expansion within the effects and causes while grouping the effects and causes under common failure modes. This inverter failure mode of not sending a PDO timeout message occurs when the inverter does not receive the proper messages from the HVSC and motor, yet does not send the proper PDO timeout message to indicate a fault has occurred.

4.4.5 Motor System Effects of the Failure Modes

The effects of the failure modes for the motor DFMEA are generated by evaluating the block diagram and connections, as well as the overall subsystem failure modes known by the FMEA team from prior motor experience. Table 4-13 shows the selected highest RPN mechanical and inverter system risk items with their effects of failure. These effects are to be evaluated on all levels of the customer requirements for the vehicle and the motor system individually.

Table 4-13: Effects of Failure Modes of most critical RPNs for Motor System

Subsystem	Interface	Design Function	Failure Mode	Effect of Failure (Local/Global)
Motor shaft	Spline Connections	Provide concentric connection and desired torque transmission between center bearing and rear differential	Non-concentric connection fails to transmit driver demanded torque	Local – vibration and misalignment of driveline components. Decreased performance of motor system Global – Early unplanned maintenance and high probability of driveline failure – Vehicle inoperable
Inverter	Communication Input	The Inverter shall send a PDO timeout message	The inverter does not send PDO timeout message when appropriate	Local – Inverter continues function last received message Global - If driver accelerating or using regenerative braking, this failure will lead to undesired motor torque

The potential effect of the failure mode of the motor shaft affects both the local motor system and the vehicle system. On a local scale the eccentric drive shaft will lead to unexpected and undesired vibration of the motor and motor shaft. This vibration has a direct impact on the performance and output of the motor system. When this vibration and misalignment occur, the vehicle will need to be serviced earlier than expected and depending on the extent of the misalignment, the entire driveline can fail – disabling vehicle propulsion in all operational modes. Secondly, the effect of the inverter failing to send a PDO timeout message is largely dependent upon the current operation of the vehicle. In this event, the inverter will continue to function using the previously received messages from the HVSC. This leaves the potential for the previously received message to be driver demanding increased torque to accelerate or brake. Without additional safety systems in place if either of those signals were received and the inverter did not send a PDO timeout message, the inverter would continue to send undesired motor torque signals to the motor and effectively for the vehicle.

4.4.6 Motor System Severity Rankings

The severity of the failure modes for the motor DFMEA are generated internally with the motor team and derived by evaluating effects of the failure mode. The scale developed and shown in Section 3.5.6 is used to objectively assign severity rankings. Table 4-14 describes the selected highest RPN mechanical and inverter system risk items with the associated severity rankings of the failure effect.

Table 4-14: Effects of Failure Modes of most critical RPNs for Motor System

Subsystem	Part	Design Function	Failure Mode	Effect of Failure (Local/Global)	Severity Ranking
Motor shaft	Spline Connections	Provide concentric connection and desired torque transmission between center bearing and rear differential	Non-concentric connection fails to transmit driver demanded torque	Local – vibration and misalignment of driveline components. Decreased performance of motor system Global – Early unplanned maintenance and high probability of driveline failure – Vehicle Inoperable	8
Inverter	Communication Input	The Inverter shall send a PDO timeout message	The inverter does not send PDO timeout message when appropriate	Local – Inverter continues to function of last received message Global - If driver accelerating or using regenerative braking this failure will lead to undesired motor torque	10

A severity rating of eight is assigned for failing to provide a concentric connection for the motor shaft. The ranking of eight is given because the failure directly impacts the primary function of the vehicle and render the vehicle inoperable. However, a severity ranking of nine or ten is unnecessary as this failure would not cause unsafe operation of the vehicle. In this event, the vehicle safety systems would still be functional and the driver would be able to come to a complete stop safely. For this effect, there are varying levels of misalignment that would affect the vehicle in different manners. The FMEA team handled this by assigning a severity rating based upon the worst possible case scenario. For the inverter failure mode effect of undesired torque, a unanimous severity rating of 10 was assigned as the standard for rating effects states whenever undesired torque or safe vehicle operation is affect the severity is immediately a 10.

4.4.7 Motor System Potential Causes

The potential causes of the failure modes for the motor DFMEA are generated internally with the motor team and derived in part by evaluating effects of the failure mode. These causes are aimed to describe the root cause of the failure mode and not downstream causes. For the mechanical systems and parts of the inverter system, the causes are listed as physical causes. However with the controller requirements potential causes may be a result of improper control code or the physical assembly of the wire harness. For this reason, both physical and virtual causes are considered for the inverter subsystem. Table 4-15 shows the selected highest RPN mechanical system and inverter system risk items with the associated potential causes for the failure mode. In Table 4-15 the failure effect and severity rating have been hidden to emphasize the potential cause should be directed at the failure mode and not the effect.

Table 4-15: Causes of Failure Modes of most critical RPNs for Motor System

Subsystem	Part	Design Function	Failure Mode	Potential Cause
Motor shaft	Spline Connections	Provide concentric connection and desired torque transmission between center bearing and rear differential	Non-concentric connection fails to transmit driver demanded torque	Improper alignment within vehicle from spline specification
Inverter	Communication Input	The Inverter shall send a PDO timeout message	The inverter does not send PDO timeout message when appropriate	Overloaded CAN bus

The determined potential cause of the spline connection is an improper alignment of the motor shaft within the vehicle. The spline selected for the motor shaft is identical to the spline used on the input of the rear differential. This spline however was never intended by the OEM to be used to transfer the rated torque and retain concentricity with a motor shaft in the middle of the driveline. This cause is not the result of human error in selecting the wrong spline, but rather the design decision to implement stock components and designs when possible within a new design. The potential cause of the inverter failing to send a PDO message is an overload of the CAN bus. In the event that the CAN bus is overloaded, there would be missed CAN messages between the inverter and the HVSC.

4.4.8 Motor System Failure Mode Occurrence Ratings

The occurrence of the failure modes for the motor DFMEA are generated internally with the motor team and derived in part by evaluating the cause of the failure mode. The scale developed and shown in section 3.4.8 is used to objectively assign occurrence rankings. Table 4-16 provides the selected highest RPN mechanical system and inverter system risk items with the associated occurrence rankings of the failure cause.

Table 4-16: Occurrence Ratings for Failure Modes of most critical RPNs

Subsystem	Part	Design Function	Failure Mode	Potential Cause	Occurrence
Motor shaft	Spline Connection	Provide concentric connection and desired torque transmission between center bearing and rear differential	Non-concentric connection fails to transmit driver demanded torque	Improper alignment within vehicle from spline specification	7
Inverter	Communication Input	The Inverter shall send a PDO timeout message	The inverter does not send PDO timeout message when appropriate	Overloaded CAN bus	5

An occurrence rating of seven is assigned to the cause of failing to provide a concentric connection for the motor shaft because similar designs used in past student designed motor applications and use of splines for the transfer of torque have resulted in frequent failures. While the spline is being used in a new application for the design intent, the spline will still be used in a similar fashion, with similar specifications and purpose from the original design intent. The combination of the two requires the FMEA team to be uncertain with the motor shaft spline connection with the changes in operating conditions and application. For the inverter failure mode cause of an overloaded CAN bus, an occurrence rating of five is assigned based upon team experience with designing, monitoring, and implementing an additional torque source onto the CAN bus.

4.4.9 Motor System Failure Mode – Prevention and Detection Methods

The prevention methods for the mechanical motor systems are the tools, software, analysis, and methods that are currently actionable by the team to reduce the frequency of the cause. The detection methods for the motor system are similar in that this DFMEA limited detection methods to ways currently used by the team to detect the failure mode causes as the effects occur. Shown in Table 4-17 are the selected highest RPN mechanical and inverter system risk items with the current prevention methods of the failure cause. The design function was removed from the table to emphasize the prevention and detection methods are to be applied to the cause of the failure, not the failure itself.

Table 4-17: Occurrence Ratings for Failure Modes of most critical RPNs

Subsystem	Part	Failure Mode	Mechanism of Failure	O	Prevention Method	Detection Method
Motor shaft	Spline Connections	Non-concentric connection fails to transmit driver demanded torque	Improper alignment within vehicle from spline specification	7	None	Visual inspection during vehicle operation – In vehicle testing
Inverter	Communication Input	The inverter does not send PDO timeout message when appropriate	Overloaded CAN bus	5	Place Electric Torque on separate CAN bus	HVSC shall monitor CAN bus loading to determine if signals are being lost

For the motor shaft spline connection, the team currently has no preventative measures in place to ensure that the misalignment and proper torque transmission occur. For the inverter cause of an overloaded CAN bus, the current prevention method is to place the electric torque signals on a separate CAN bus to reduce the likelihood of overloading the bus. For many of the risks of the motor system, a simple and effective method of preventing various risks and failure modes is to have an additional member, knowledgeable in the area, to check over the design work.

The current detection method for improper alignment and spline specifications are only during vehicle testing. This is due to the lack of equipment and software to test the motor shaft-drive shaft connection prior to vehicle integration. The HVSC will be used to monitor CAN bus loading levels to determine if any signals are being lost and detect if any PDO messages are missing.

4.4.10 Motor System Failure Mode Detection Ratings

The detection ratings for the motor DFMEA are generated with the motor team and derived in part by evaluating cause of the failure mode. The detection rating for mechanical systems is based upon the ability of the current design controls to detect the cause of the failure. For the inverter systems the detection rating is based upon the detection methods ability to detect the failure itself. The scale developed and shown in section 3.4.11 is used to objectively assign detection rankings. Table 4-18 shows the selected highest RPN mechanical and inverter system risk items with the associated detection rankings.

Table 4-18: Detection Ratings for Failure Modes of most critical RPNs

Subsystem	Part	Failure Mode	Potential Cause	Prevention Method	Detection Method	Detection
Motor shaft	Spline Connections	Non-concentric connection fails to transmit driver demanded torque	Improper alignment within vehicle from spline specification	None	Visual inspection during vehicle operation – In vehicle testing	9
Inverter	Communication Input	The inverter does not send PDO timeout message when appropriate	Overloaded CAN bus	Place Electric Torque on separate CAN bus	HVSC shall monitor CAN bus loading to determine if signals are being lost	8

A detection rating of nine is assigned to the cause for the failure mode of failing to provide a concentric connection for the motor shaft as a result of the current detection method requires that the design reach in-vehicle testing before discovered. Similarly, the team currently has no methods to model dynamic driveline loading. The static FEA that may be performed on the driveline will not correlate to expected actual operation conditions.

The inverter detection method for determining PDO timeout messages is sent over CAN, which is able to be read during in-vehicle testing. DriveTool can be implemented to monitor bus levels during in-vehicle testing. DriveTool is a software UI developed by InMotion for motor diagnostics. DriveTool has two main functions: testing motor operation and uploading hardware parameters. Uploading new hardware parameters, provided by InMotion, allows for flashing new tunes to the inverter. From the detection rating in section 3.5.11 if the fault is not possible to simulate in MIL, SIL, or HIL, and only during in-vehicle testing, the failure mode receives a rating of eight.

4.4.11 Motor System Risk Priority Numbers, Criticality Numbers, and Thresholds

Upon completing all of the required columns for the motor system DFMEA, the RPNs, SOs, and thresholds are set. The analysis that is prescribed for the two highest RPN items is also carried out during motor system FMEA team meetings and recorded. The complete DFMEA for the motor system can be found in Appendix A. Table 4-19 presents the motor shaft and inverter communication input failure modes with severity, occurrence, detection, RPN, and SO ratings.

Table 4-19: Motor System RPN

Part	Design Function	Potential Mode	S	O	D	SO	RPN
Spline Connections	Provide concentric connection and desired torque transmission between center bearing and rear differential	Non-concentric connection fails to transmit driver demanded torque	8	7	9	56	504
Communication Input	The inverter shall send a PDO timeout message	The inverter does not send PDO timeout message when appropriate	10	5	8	50	400

As stated previously, the RPNs and SOs for all motor system risk items are relative tools and beneficial for relating risk within the motor system and the motor system alone. Upon viewing the line items developed, a universal relative threshold is determined to be irrelevant due to the combination of mechanical and inverter system failure modes within the same analysis. Therefore, two individual RPN thresholds are set: one for the mechanical systems, and one for the inverter systems.

The average RPN and the percent of risk items over the average are calculated to establish a quantifiable starting point for setting a threshold for the mechanical systems within the motor system. This analysis is done again for the inverter system. Table 4-20 shows the results of the preliminary analysis.

Table 4-20: Preliminary Analysis of Average RPNs

Motor System	Average RPN	Percent of Risk Items over Average RPN
Mechanical Systems	63	28%
Inverter Systems	111	50%

Taking the average RPN, the FMEA team discussed all risk items above the average RPN for each system starting with the highest RPNs. Shown in Table 4-21 are the five highest ranking RPN failure modes for the motor system. The causes listed are among the most common risk items, with exception to the stator core, aim to reduce the occurrence and detection ratings.

Similar analysis and discussion is conducted upon the discovery of common causes among the inverter systems and mechanical systems. A subjective analysis and discussion led to the development of recommendations actions to address inverter system RPNs above 300 and mechanical system RPNs above 100. These specific threshold holds are chosen as reducing the occurrence and detection rating of the failure modes above each respective limit would also in turn reduce a large amount of the RPN values for those failure modes below the limit. Recommended actions are only given for mechanical and inverter failure modes over the specified threshold and for common causes underneath.

Table 4-21: Top Five Motor System RPNs

No.	Subsystem	Part/Interface	Design Function	Failure Mode	Failure Effect	S	Potential Cause	O	Prevention Method	Detection Method	D	RPN
1	Motor shaft	Motor shaft/spline connection	Provides Concentric Connection Between Center Bearing and Rear differential and transmits torque	non-concentric connection fails to transmit desired torque	Drivetrain misalignment - loss of performance & comfort. Early unplanned maintenance and high probability of driveline failure - vehicle inoperable	8	Improper alignment within vehicle with improper spline specifications for rated torque	7	None	Visual inspection - in vehicle testing	9	**504**
2	Stator	Stator Laminations	Controls Air Gap	Failure to control the air gap	Interference, rubbing, noise, failure, bearing loads.	7	Outer diameter not concentric	8	Radial tolerance analysis updated with limits 1/3*Air gap	POC builds, prototype and preseries builds, assembly not possible	8	**448**
3	Inverter	Communication Input	The inverter shall send a PDO timeout message	Inverter does not send a PDO timeout message	Undesired motor torque	10	Overloaded CAN bus	5	Place CAN on separate CAN bus	HVSC shall monitor CAN bus loading to determine if signals are being lost. DriveTool can be used during vehicle testing	8	**400**
4	Inverter	Communication Input	The inverter shall send a PDO timeout message	Inverter does not send a PDO timeout message	Undesired motor torque	10	Faulty wiring between inverter and HVSC	5	Inspection from additional CSMS Member	HVSC shall verify communication with the inverter	8	**400**
5	Inverter	Communication Input	The inverter shall send a PDO timeout message	Inverter does not send a PDO timeout message	Undesired motor torque	10	Improper code in the HVSC	4	SIL and HIL testing	None - InMotion defined and programmed function	10	**400**

4.4.12 Motor System Recommended Actions

Once the highest RPNs are collected, the FMEA team began developing the recommended actions to mitigate the risk of the severity of the potential failure mode. The recommended actions are aimed to decrease the occurrence and detection rankings assigned to the failure modes. Table 4-22 shows the actions and resultant revised RPNs for the highest RPNs for the mechanical and inverter systems.

Table 4-22: Motor DMFEA Revised Ratings for Highest RPNs

Part	Design Function	Failure Mode	S	O	D	RPN	Recommended Action	S	O	D	RPN
Spline Connections	Provide concentric connection and desired torque transmission between center bearing and rear differential	Non-concentric connection fails to transmit driver demanded torque	8	7	9	504	1) Driveline modeling software to determine alignment and structural integrity of motor shaft/spines 2) Prototyping and testing of motor shaft and spline connections prior to integration into motor and vehicle	8	3	4	120
Communication Input	The inverter shall send a PDO timeout message	The inverter does not send PDO timeout message	10	5	8	400	Decrease period between signals by increasing the signal sending rate to 500 kbaud and verify with in-vehicle testing	10	3	8	240

The FMEA team considered options that are able to be immediately implemented and those that would require more time or resources to implement when developing the recommended actions. When looking at the spline connection for torque transmission with an original RPN of 504, the first action of using driveline modeling software to gain more confidence in the design for drive shaft integrity and concentricity would require HEVT to learn a new software and more likely be implemented for future years of competitions. This software testing would significantly decrease the likelihood of these events from a ranking of seven, to three, isolating the incidents to design simulations and testing. Similarly, driveline modeling software would detect driveline issues much earlier in the design process, prior to in-vehicle testing. A revised detection rating of four is assigned as a result of the software, in conjunction with the suggested prototyping and testing of the motor shaft, would allow for all defects to be caught prior to the design freeze. In order to properly incorporate prototype testing of the motor shaft, arrangements will need to be made with the motor manufacturer to develop the motor shaft early on in the process so that fatigue and failure tests can be performed prior to implementing the shaft into the motor assembly. The resultant RPN of 120 is a reduction of 76% for the specific failure mode.

The FMEA team aimed to reduce the occurrence and detection ratings for the inverter system failure mode of failing to send a PDO timeout message with a RPN of 400. The recommended actions for this failure mode is to change the calibration of the inverter baud rate from 250 kbaud to 500 kbaud the increase in baud rate allows for more data to be communicated in a given period of time, which lowers the overall bus load when the amount of data sent is held the same. By this action only the occurrence is decreased from a five to a three with the decreased level of likelihood that the decreased period the CAN bus will be overloaded and signals will be missed. The detection rating and severity remain unchanged for any currently known recommended actions to alleviate this failure mode. Monitoring software DriveTool can be used while performing in-vehicle testing to monitor bus levels, but has not currently been implemented by the team. DriveTool communication setup allows for testing of motor functionality without the need of a full vehicle, but can be used during in-vehicle testing to monitor CAN bus loading levels. Using DriveTool during in-vehicle testing will require significant wiring additions to the current low voltage wiring harness. The revised RPN of 240 is a 40% reduction from the original 400 for the inverter system.

4.4.12.1 Mechanical System Recommendations

For the mechanical system the single greatest recommended action to reduce risk is the implementation of a dynamic driveline modeling software. The most severe risks involve functions of components that require precise alignment or specification for the amount of torque being transmitted through or by the component. This software is to be implemented, early on in the design phase to detect and validate the design of torque couplings, spline patterns and hardening specifications, and other driveline components. The author suggests the use of software such as SimDriveline by MATHWORKS or Adams by MSC software (Software 2016). These softwares will allow team members to manage and evaluate the interactions between motion, structures, and controls to improve the vehicle design for safety, performance, and consumer acceptability. Once learned and implemented the amount of time required for traditional static-linear FEA solutions through nonlinear dynamics that utilize multibody dynamics solvers.

The software allows for the analysis of flexible body integration for suspension, driveline, and other vehicle components where deformation effects are critical to a proper analysis and the assumption of a rigid body is not valid. In addition these programs offer durability analysis which will allow the engineer to analyze the strain, stress, and expected life of a component. Finally, vibration analysis for a motor system and overall vehicle will allow teams to relate frequencies developed throughout the car to ensure that all noise, vibration, and harshness (NVH) prior to the initial vehicle testing (Software 2016). The overall impact of this software cannot be truly pictured through the motor system alone, but a systems level adoption of this software would greatly improve the designs of all mechanical components by allowing for cost free, predesign freeze testing and validation. Once implemented, the motor system and all vehicle system DFMEAs should be reevaluated.

4.4.12.2 Inverter System Recommendations

While overloading the CAN bus may result in the highest risk for the inverter system, the most impactful recommended actions for mitigating controller risk is to verify all connections in the wire harnesses prior to and after the assembly, and proper adherence to the control code development process. By establishing a standard for the development of wire harnesses, proper training for pinning, depinning, soldering, and removing connectors, a large majority of the risks associate with a faulty wire harness are mitigated.

These procedures must be implemented in conjunction with strict adherence to the controller specification sheet to verify pin location and then be approved by another member after review of the connections made. Pin diagrams for existing connectors should be standardized and implemented to ensure understanding between all members working on the wire harness of the inverter or any vehicle system. Finally, by properly developing the controller SIL before advancing to HIL testing, the team is able to confirm communication behavior without introducing the potential for a problem with the wiring harness. In addition SIL is able to run in simulation time which reduces overall testing duration. Once the SIL model is refined, an HIL model benefits in being fully developed by allowing for testing the I/O structure of components in real time. HIL gives opportunity to validate the wiring harness and control code before vehicle integration and testing. By adhering to the proper control code development process, risks are detected earlier in the design process, and the likelihood of some potential downstream risks are dissolved completely.

Both mechanical and inverter recommended actions focus on the implementation of methods early in the design process to reduce and detect potential failure modes. The proposed actions not only reduce motor and vehicle system risk, but provide students with a greater educational experience by exposing them to a more thorough design methodology through advanced tools and refined practices. While the implementation of these methods earlier in the design phase will allow for reduced risk, the timing of the project must be kept in mind to ensure that large milestones are still being met. This project management requires a balance of design refinement and overall system progress which is to be managed effectively by leadership members.

After revising all list items with common causes and effects as the team determined revised thresholds and the resultant reductions in RPN. This risk reduction can be quantified and seen in Table 4-23.

Table 4-23: Motor System DMFEA Projected Revised Ratings

Motor System	**Original**		**Revised**			
	Average RPN	**Percent of Risk Items over Average RPN**	**Average RPN**	**Percent of Risk Items over Average RPN**	**% Over Original Average RPN**	**RPN Reduction %**
Mechanical Systems	63	28%	47	47%	21%	25%
Inverter Systems	112	50%	74	48%	30%	34%
Combined	97	41%	66	41%	27%	32%

The average RPNs of the mechanical and inverter systems are reduced to 47% and 48% respectively. The overall reduction in risk for the entire motor system through the prescribed recommended actions is 32%. This reduction can only be viewed as relative to the motor system and should not be considered the final review of the motor DFMEA. For the current timing of the project, awaiting the prototype motor delivery, the author suggests that this DFMEA be continually updated throughout bench testing and in-vehicle testing of the motor system to more accurately track and evaluate risk.

5 Conclusion

This work set out to provide a methodology and thorough example for how DFMEA can be used effectively within a student competition project setting for the advancement of the project and the student's education. Upon reviewing the goals set out in Section 1.5, this thesis completely accomplished all desired targets. Starting off, a DFMEA methodology, worksheet, and definitions have been defined. DFMEA is a difficult process to implement for corporations and students a-like due to the subjective and relative nature of the analysis and the amount of required time to perform. The model provided from this work allows teams to step through the required actions in the development of a DFMEA by organizing each of the major attributes of a FMEA in a systematic "column by column" manner. The application of this model is tailored to timelines such as those represented in the EcoCAR 3 VDP. The creation of naming and number convention for DFMEA will allow vehicle systems to be properly documented and tracked throughout the development of the vehicle. The common ranking definitions and criteria for both mechanical and controller systems allows component systems to be analyzed and evaluated for risk relative to one another instead of solely as an isolated system. Once all systems have been analyzed, students are able to clearly see the systems and components that require immediate action to reduce the overall risk of the project.

In addition to the model itself, the analysis within this work successfully identified, defined, and related varying levels of customer requirements, subsystem, and component functions. The four customers identified are the end-user, governing organizations, supplier, and internal customers, and are thoroughly explained through the P3 motor system analysis. While the end user and governing organizations may dictate the intended direction of the vehicle as a whole, compromises must be made throughout the supplier capabilities and component limitations to accommodate all requirements as best as possible. For the P3 motor, the peak torque output of 640 Nm could not be accommodated while still complying with the EcoCAR 3 NYSR for NCZs. The compliance with customer specifications required the reduction of the size and peak torque output of the motor to 500 Nm. In order to maintain the performance desired by the end user, quantified as being able to complete the EcoCAR 3 4-cycle in CD, the base speed of the motor was raised from 1500 Nm to 1900 Nm to ensure a similar power output of 100 kW.

The motor system applied to the DFMEA model is divided first into the mechanical and inverter subsystems from which components and interfaces are identified. These interfaces and connections are then considered to be the design functions and analyzed the potential failures of the parts. The definitions for severity, occurrence, and detection were applied to the each failure mode effects, causes, and detection methods, respectively. These rankings are then combined to provide the collective RPN and SO rankings of the entire motor system. A mechanical system average RPN of 63 is found, with an inverter system average RPN of 112. After analyzing risk items above the respective averages and overall highest RPNs, recommendation actions are provided to reduce the occurrence and detection rankings for the critical risk items. Mechanical systems can best be mitigated by the implementation of vehicle dynamics modeling software such as Adams. Such software will allow for earlier modeling of critical driveline components and simulate real world nonlinear driving forces. Inverter system risk is reduced with strict adherence to the control code development process. By progressing from MIL to SIL, SIL to HIL, and HIL to in-vehicle testing, the number of potential risks are reduced when each preceding stage is validated prior to advancing. In conjunction with proper training for the development and documentation of wire harnesses, proper control code development will reduce inverter system risks. By implementing the recommended actions the mechanical system average RPN is reduced to 47, a reduction of 25%. Similarly the inverter system average RPN is reduced from 112 to 74, a reduction of 34%. The combined average RPN reduction for the entire motor system is 32%, from 97 to 66. These reductions are projections for after the recommended actions are implemented.

5.1 Future Work

In order for this work to be truly utilized at the fullest potential there are additional actions required. First, the analysis performed on the motor system must also then be performed on all vehicle systems as prescribed in Table 4-6. From experience and familiarity with the complexity of vehicle systems the author recommends the engine and ESS to be the next components systems to undergo thorough analysis. While all remaining subsystems must be analyzed prior to a true vehicle specific RPN or SO threshold, the thresholds can be adjusted as more information is gathered on any subsystem. Once the vehicle specific RPN and SO thresholds are determined, the values should be constantly refined and discusses as more information is available to improve the meaning of the thresholds. The vehicle specific RPN should then be compared with similar vehicle RPNs developed by the team. After multiple comprehensive vehicle DFMEAs have been conducted, the resultant vehicle specific thresholds can be related and a universal RPN and SO threshold can be set for hybrid vehicle systems in a student competition environment.

In addition to the development and setting of the universal RPN thresholds, more quickly actionable work exists where this work leaves off. Within student competitions such as EcoCAR 3, there are competition points related to the customer requirements described in Table 1-2. Depending on the current component system undergoing analysis, the component functionality make impact various specifications required by customers. These impacts on requirements can and should be translated as closely as possible to the point reduction experienced due to a particular failure mode or risk line item. By quantifying the failure mode impact not only on vehicle and component performance, but on team success and standing within a competition will provide important information early on in the design process when inherent trade-offs will be identified between and within individual component systems. For EcoCAR 3, relating risks to points and events would require relating each risk item to the relevant VTS and then the specific event at competition that validates the vehicle to design intent.

Finally, vehicle and component cost and timing should be thoroughly examined through a SFMEA. Vehicle SFMEA will provide overall product goals, end user requirements, and governing organization specifications that encompass all component systems within the vehicle but more specifically the vehicle as a whole. Component SFMEA will relate the vehicle requirements down to the component being analyzed to provide understanding of how vehicle requirements affect individual components. Important considerations for initial design costs of the vehicle and components provide guidance for which systems require more simulation prior to building, and which are more accurately and effectively designed through prototyping. Project cost and timing must be balanced with team experience and overall risk involved in the project. The future work for this model is continually refine and improve every definition and criteria, as more component systems are analyzed, to provide a comprehensive risk analysis that will provide future teams adequate understanding of the risks involved in various design choices.

5.2 Summary

This thesis has achieved each objective prescribed at the beginning of this work. A repeatable and actionable method of DFMEA for a competition team setting is defined and implemented. The completed DFMEA on the custom P3 Motor for EcoCAR 3 is achieved through the application of the developed method. While no universal threshold is set, motor system specific thresholds are set for the mechanical and inverter systems, respectively. Upon application of this method to all vehicle systems, a vehicle specific RPN and SO threshold would be applicable and relevant. Additionally, the most critical risk items were given recommended actions of dynamic software application and proper control code development to ensure motor system and vehicle functionality. Finally, a strategy is suggested for implementing the various phases of FMEA into a multi-year design project. The spirit of this thesis is to provide a thorough case study and application of DFMEA as a tool to assist in the education and growth of the next generation of automotive engineers.

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Appendix A: Mechanical Motor Design Requirements

Table A-1: Motor Mechanical System Functional Requirements

Component(s)	Requirement	Specification
Bearings	Handle Axial Loading	
	Handle Weight of Rotor & Shaft	~29.5 kg
	Isolate Engine/Braking Torque from Motor Housing	
	Bearing ID = Shaft OD	65 mm
	Bearing OD = Endbell ID	100 mm
	Wave spring on output bearing	Fits 100 mm bore, 2.77 mm working height, 4.57 free height, 276 N load, Spring constant 157 N/mm
Bearing clamps	Preloads bearing so bearing spins, doesn't slide. Preventing outer races from spinning	
	Maintains bearing position	
	Must constrain outer race without interfering with inner	ID = 92 mm
Terminal Box	Watertight seal	
	Isolate terminals w/ ecap to prevent grounding to housing	
	Allow for 3 phase lines to maintain specified BR	
Terminal Box Lid	Watertight Seal	
	Strain relief for cables	
End Bell - Input	House resolver stator	Resolver Housing ID = 138 mm
	drain hole for water	
	Allow for resolver calibration (rotation)	70 degrees
	House LV Connector	Digikey AD38999/20FB35PNLC-ND
	Endbell ID = Bearing OD	100 mm
	Through holes for bearing clamps	
	Through holes for temperature sensor	
	groove for O-ring	
	Package with constrained area	270OD X 300L (mm)
End Bell - Output	Through holes for terminals	
	Endbell ID = Bearing OD	100 mm
	groove for O-ring	ID = 246 mm, OD = 254 mm, Width - 7.2 mm
	Package with constrained area	270OD X 300L (mm)
Housing	Shoulder to locate stator core	ID = 234.45 mm, OD = 239.45 mm
	Allow for vehicle mounting	
	Provide Passive Air Cooling	
	Provides water tight seal	
	Package with constrained area	300OD x 280 L (mm)
Floorpan modification	Support Motor Assembly weight	
	Support reaction torque	
	Pass ANL Waiver Requirements	
	Accept motor mounts	
Motor Mounts	Provide Vibration Isolation	
	React Torque	
	Position motor	

Component(s)	Requirement	Specification
	Support weight of motor assembly	
3 - Phase	Transmit Current	
	Maintain Supplier BR	
LV Harness	Transmit Current	
	Maintain Supplier BR	
Shaft	Keyed shoulder for rotor assembly	
	snap rings grooves	
	shoulder for resolver rotor adapter	
	Threads for lock nut	
	Bearing shoulders	
	Transmit Engine + Motor Torque	
	Maintain Driveline Concentricity	
	Radii to less development of stress concentrations	
	Spline hardening	
	Spline pattern	
	Male Pilot	
Resolver Stator	Stator OD accepted by Endbell	
	Rotational Freedom for calibration	
Resolver Rotor	Rotor ID = Adapter OD	
	# Resolver Rotor Poles be integer multiple of Stator Poles	
Resolver Clamp	Secure Resolver to Endbell	
Resolver Adapter	Couple Resolver Rotor to Shaft	
	Adapter OD = Resolver Rotor ID	
Rotor Lams	Keyed Connection to Motor shaft	
	Through holes for retaining plates	
	Secure magnets	
Stator Lams	Secure and Insulate windings	
	Provide airgap between Rotor	~0.5 mm
	Shrink fit to housing	
Stator Windings	Create Magnetic Field	
	Package within Laminations	
	Terminate on same side as Terminal Box	
	# Resolver Rotor Poles be integer multiple of Stator Poles	

Appendix B: Complete DFMEA

Table B-1: Complete Motor System DFMEA

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
1	Motorshaft	Motorshaft/spline connection	Provides Concentric Connection Between Center Bearing and Rear differential and transmits torque	non-concentric connection fails to transmit desired torque	Drivetrain misalignment - loss of performance & comfort. Early unplanned maintenance and high probability of driveline failure - vehicle inoperable	8	Improper alignment within vehicle with improper spline specifications for rated torque	7	None	Visual Inspection - In Vehicle Testing	9	**504**
2	Stator	Stator Core Bonded & Machined	Controls Air Gap	Failure to control the air gap	Interference, rubbing, noise, failure, bearing loads.	7	Outer diameter not concentric	8	Radial tolerance analysis updated with limits 1/3*Air gap	POC builds, prototype and preseries builds, Assembly not possible	8	**448**
3	Inverter	Communication Input	The inverter shall send a PDO timeout message	Inverter does not send a PDO timeout message	Undesired motor torque	10	Overloaded electric torque bus	5	Place electric torque on separate bus	HVSC shall monitor bus loading to determine if signals are being lost. DriveTool can be used during vehicle testing	8	**400**
4	Inverter	Communication Input	The inverter shall send a PDO timeout message	Inverter does not send a PDO timeout message	Undesired motor torque	10	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HVSC shall verify communication with the inverter	8	**400**
5	Inverter	Communication Input	The inverter shall send a PDO timeout message	Inverter does not send a PDO timeout message	Undesired motor torque	10	Improper code in the HVSC	4	SIL and HIL testing	None - InMotion defined and programmed function	10	**400**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
6	Inverter	Communication Output	The inverter shall send the operation time output	Inverter does not send operation time output	Undesired motor torque	10	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HVSC shall monitor bus loading to determine if signals are being lost. DriveTool can be used during vehicle testing	8	**400**
8	Inverter	Start Up	The inverter shall be verified by the HVSC that it is not transmitting faults. If the inverter is transmitting faults they must be identified, resolved, and cleared before proceeding	Inverter does not transmit faults	Motor System Disabled	7	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	None - InMotion defined and programmed function	10	**350**
11	Motorshaft	Motorshaft/spline connection	Transmit requested Torque	Fails to Transmit required torque	Loss of primary function, vehicle inoperable	8	Improper spline specified on drawing	4	None	Visual Inspection - In Vehicle Testing	10	**320**
12	Motorshaft	Motorshaft/spline connection	Transmit requested Torque	Fails to Transmit required torque	Loss of primary function, vehicle inoperable	8	Inadequate spline engagement between male and female splines	5	None	Visual Inspection - In Vehicle Testing	8	**320**
13	Inverter	Communication Output	The inverter shall send the feedback sensor message	Inverter does not send the feedback sensor message	Unknown torque produced	10	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HVSC shall verify communication with the inverter	6	**300**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
14	Inverter	Communication Output	The inverter shall send the torque reference manager message	Inverter does not send the torque reference manager message	Unknown actual torque produced by motor	10	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HVSC shall verify communication with the inverter	6	**300**
15	Inverter	Communication Output	The inverter shall send the torque current limit message	Inverter does not send the torque current limit message	Too much torque produced by motor	10	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HVSC shall verify communication with the inverter	6	**300**
16	Inverter	Communication Output	The inverter shall send the torque current limit message	Inverter does not send the torque current limit message	Too little torque produced by motor	10	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HVSC shall verify communication with the inverter	6	**300**
17	Inverter	Emergency Response	The inverter shall receive a zero torque command from a HVSC CAN message	The inverter does not receive a zero torque command from the HVSC	Unintended acceleration	10	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HIL Testing	6	**300**
18	Inverter	Inverter I/O - Pin 19	HVIL Out	Short To Logic	Downstream components continue to function without HVIL influence	10	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC receives error SDO	6	**300**
19	Inverter	Inverter I/O - Pin 20	HVIL In	Short To Logic	Inverter & Downstream components continue to function without HVIL influence	10	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**300**
20	Inverter	Start Up	The inverter CAN message communication shall be verified by the HVSC	Communication is not verified by the HVSC	Unknown if the Inverter is receiving messages from the HVSC	6	High Voltage noise	6	Wire Shielding	HVSC shall send a signal to the driver if communication is not verified	8	**288**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
21	Inverter	Communication Input	The inverter shall receive a torque command from the HVSC	Inverter does not receive the torque command from the HVSC	Loss of motor torque	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC shall verify communication with the inverter	8	**280**
22	Inverter	Inverter I/O - Pin 34	High side out GND	Short To Logic	Motor System Disabled - performance decreased	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	In vehicle testing	8	**280**
23	Inverter	Start Up	The inverter shall be verified by the HVSC that it is not transmitting faults. If the inverter is transmitting faults they must be identified, resolved, and cleared before proceeding	Faults are not resolved	Motor System Disabled	7	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	Inspection by team member if faults are still being transmitting	8	**280**
24	Inverter	Communication Input	The inverter shall send a PDO timeout message	Inverter does not send a PDO timeout message	Inverter overheats	5	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	None - InMotion defined and programmed function	10	**250**
25	Inverter	Communication Input	The inverter shall send a PDO timeout message	Inverter does not send a PDO timeout message	Motor overheats	5	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	None - InMotion defined and programmed function	10	**250**
26	Inverter	Emergency Response	The inverter shall receive a zero torque command from a HVSC CAN message	The inverter does not receive a zero torque command from the HVSC	Unintended acceleration	10	Improper code in the HVSC	4	SIL and HIL testing	HIL Testing	6	**240**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
27	Inverter	Start Up	The inverter shall receive 12V power	Inverter does not receive 12 V power for start up	Inverter does not start up	5	Power relay is not triggered/tripped to send power to the inverter	6	Send CAN Message to activate relay	HVSC shall verify communication with the relay box	8	**240**
28	Inverter	Inverter I/O - Pin 19	HVIL Out	Open	Motor System Disabled - Vehicle Inoperable	8	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**240**
29	Inverter	Inverter I/O - Pin 20	HVIL In	Open	Motor System Disabled - Vehicle Inoperable	8	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**240**
30	Inverter	Inverter I/O - Pin 01	Motor Temperature Sensor 2	Short To Ground	Inverter Fault Motor System functionality reduced - 50% current	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
31	Inverter	Inverter I/O - Pin 01	Motor Temperature Sensor 2	Short To Logic	Inverter Fault Motor System functionality reduced - 50% current	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
32	Inverter	Inverter I/O - Pin 01	Motor Temperature Sensor 2	Open	Inverter Fault Motor System functionality reduced - 50% current	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
33	Inverter	Inverter I/O - Pin 02	Motor Temperature Sensor 1 GND	Short To Logic	Inverter Fault Motor System functionality reduced - 50% current	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
34	Inverter	Inverter I/O - Pin 02	Motor Temperature Sensor 1 GND	Open	Inverter Fault Motor System functionality	7	Improper wire harness assembly	5	Component Specification	HVSC detects Inverter Fault	6	**210**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
					reduced - 50% current				Documents and Proper Training			
35	Inverter	Inverter I/O - Pin 03	Motor Temperature Sensor 1	Short To Ground	Inverter Fault Motor System functionality reduced - 50% current	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
36	Inverter	Inverter I/O - Pin 03	Motor Temperature Sensor 1	Short To Logic	Inverter Fault Motor System functionality reduced - 50% current	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
37	Inverter	Inverter I/O - Pin 03	Motor Temperature Sensor 1	Open	Inverter Fault Motor System functionality reduced - 50% current	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
38	Inverter	Inverter I/O - Pin 04	Motor Temperature Sensor 2 GND	Short To Logic	Inverter Fault Motor System functionality reduced - 50% current	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
39	Inverter	Inverter I/O - Pin 04	Motor Temperature Sensor 2 GND	Open	Inverter Fault Motor System functionality reduced - 50% current	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
40	Inverter	Inverter I/O - Pin 05	Resolver Chassis (Shield)	Short To Logic	Inverter Fault - Motor System Disabled - Decreased Vehicle Performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
41	Inverter	Inverter I/O - Pin 05	Resolver Chassis (Shield)	Open	Inverter Fault - Motor System Disabled - Decreased	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
					Vehicle Performance							
42	Inverter	Inverter I/O - Pin 06	Resolver excitation +	Short To Ground	Inverter Fault - Motor System Disabled - Decreased Vehicle Performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
43	Inverter	Inverter I/O - Pin 06	Resolver excitation +	Short To Logic	Inverter Fault - Motor System Disabled - Decreased Vehicle Performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
44	Inverter	Inverter I/O - Pin 06	Resolver excitation +	Open	Inverter Fault - Motor System Disabled - Decreased Vehicle Performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
45	Inverter	Inverter I/O - Pin 07	Resolver COS+	Short To Ground	Inverter Fault - Motor System Disabled - Decreased Vehicle Performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
46	Inverter	Inverter I/O - Pin 07	Resolver COS+	Short To Logic	Inverter Fault - Motor System Disabled - Decreased Vehicle Performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
47	Inverter	Inverter I/O - Pin 07	Resolver COS+	Open	Inverter Fault - Motor System Disabled - Decreased	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
					Vehicle Performance							
48	Inverter	Inverter I/O - Pin 08	Resolver COS-	Short To Ground	Inverter Fault - Motor System Disabled - Decreased Vehicle Performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
49	Inverter	Inverter I/O - Pin 08	Resolver COS-	Short To Logic	Inverter Fault - Motor System Disabled - Decreased Vehicle Performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
50	Inverter	Inverter I/O - Pin 08	Resolver COS-	Open	Inverter Fault - Motor System Disabled - Decreased Vehicle Performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
51	Inverter	Inverter I/O - Pin 09	Resolver excitation -	Short To Ground	Inverter Fault - Motor System Disabled - Decreased Vehicle Performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
52	Inverter	Inverter I/O - Pin 09	Resolver excitation -	Short To Logic	Inverter Fault - Motor System Disabled - Decreased Vehicle Performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
53	Inverter	Inverter I/O - Pin 09	Resolver excitation -	Open	Inverter Fault - Motor System Disabled - Decreased	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
					Vehicle Performance							
54	Inverter	Inverter I/O - Pin 10	Resolver SIN+	Short To Ground	Inverter Fault - Motor System Disabled - Decreased Vehicle Performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
55	Inverter	Inverter I/O - Pin 10	Resolver SIN+	Short To Logic	Inverter Fault - Motor System Disabled - Decreased Vehicle Performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
56	Inverter	Inverter I/O - Pin 10	Resolver SIN+	Open	Inverter Fault - Motor System Disabled - Decreased Vehicle Performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
57	Inverter	Inverter I/O - Pin 11	Resolver SIN-	Short To Ground	Inverter Fault - Motor System Disabled - Decreased Vehicle Performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
58	Inverter	Inverter I/O - Pin 11	Resolver SIN-	Short To Logic	Inverter Fault - Motor System Disabled - Decreased Vehicle Performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
59	Inverter	Inverter I/O - Pin 11	Resolver SIN-	Open	Inverter Fault - Motor System Disabled - Decreased	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
					Vehicle Performance							
60	Inverter	Inverter I/O - Pin 19	HVIL Out	Short To Ground	Inverter Fault - Motor System Disabled - Decrease Performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
61	Inverter	Inverter I/O - Pin 20	HVIL In	Short To Ground	Inverter Fault - Motor System Disabled - Decrease Performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	6	**210**
62	Inverter	Start Up	The inverter shall be verified by the HVSC that it is not transmitting faults. If the inverter is transmitting faults they must be identified, resolved, and cleared before proceeding	HVSC does not verify that the inverter is transmitting faults	Motor System Disabled	7	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HVSC shall verify communication with the inverter	6	**210**
63	Inverter	Communication Input	The inverter shall receive the motor speed from the resolver sensor	Inverter does not receive the motor speed from the resolver	Unknown actual torque produced by motor	10	Faulty resolver	2	None - Supplier Inspection	Inverter shall verify that the resolver is transmitting motor speed	10	**200**
64	Inverter	Communication Input	The inverter shall receive the motor speed from the resolver sensor	Resolver sensor does not send motor speed	Unknown actual torque produced by motor	10	Faulty resolver	2	None - Supplier Inspection	Inverter shall verify that the resolver is transmitting motor speed	10	**200**
65	Inverter	Communication Input	The inverter shall receive the	Inverter does not receive motor speed	Unknown actual torque	10	Damaged resolver	2	None - Supplier Inspection	Inverter shall verify that the	10	**200**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
			motor speed from the resolver sensor		produced by motor					resolver is transmitting motor speed		
66	Inverter	Communication Input	The inverter shall send a PDO timeout message	Inverter does not send a PDO timeout message	Inverter overheats	5	Improper code in the HVSC	4	SIL and HIL testing	None - InMotion defined and programmed function	10	**200**
67	Inverter	Communication Input	The inverter shall send a PDO timeout message	Inverter does not send a PDO timeout message	Motor overheats	5	Improper code in the HVSC	4	SIL and HIL testing	None - InMotion defined and programmed function	10	**200**
68	Inverter	Start Up	The inverter shall receive 12V power	Inverter does not receive 12 V power for start up	Inverter does not start up	5	Faulty wiring between power relay and inverter	5	Inspection from additional CSMS Member	HVSC shall send a signal to the driver establishing that the inverter is not started	8	**200**
69	Inverter	Start Up	The inverter shall receive 12V power	Inverter does not receive 12 V power for start up	Inverter does not start up	5	Faulty wiring between HVSC and power relay	5	Inspection from additional CSMS Member	HVSC shall verify communication with the relay box	8	**200**
70	Inverter	Start Up	The inverter shall receive adequate dc voltage from the High Voltage Bus to enable power mode	Inverter does not receive adequate dc voltage to enable power mode	Inverter is not enabled	5	Faulty wiring between ESS and Inverter	5	Inspection from additional CSMS Member	In Vehicle Testing - HVSC Status message with Bus Voltage	8	**200**
71	Stator	Stator Core Bonded & Machined	maintain parallel stack	stack is not parallel	loss of torque& poor performance	2	incorrect perpendicularity called out	10	none	No detection method	10	**200**
72	Motorshaft	Motorshaft/spline connection	Transmit requested Torque	Fails to Transmit required torque	Loss of primary function, vehicle inoperable	8	Improper spline hardening specified	3	quality control, utilize OEM design, verify spline specifications for estimated torque output through vehicle	Visual Inspection - In Vehicle Testing	8	**192**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
73	Inverter	Communication Output	The inverter shall send the DC power limit	Inverter does not send the DC power limit	Inverter operates outside of safe operation range	9	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HVSC shall verify communication with the inverter	4	**180**
74	Inverter	Communication Output	The inverter shall send the DC power limit	Inverter does not send the DC power limit	Motor operates outside of safe operation range	9	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HVSC shall verify communication with the inverter	4	**180**
75	Stator	Slot Insulation	insulates magnet wire from core	Fails to insulate	Winding short - Motor fails - shock hazard	9	Incorrect dimensions	10	stator lam & component layout & proto build	POC builds, prototype and preseries builds	2	**180**
76	Inverter	Inverter I/O - Pin 29	CAN Open L	Short To Ground	CAN Bus inoperable - Motor System disabled - decrease performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault during HIL Set up	5	**175**
77	Inverter	Inverter I/O - Pin 29	CAN Open L	Short To Logic	CAN Bus inoperable - Motor System disabled - decrease performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault during HIL Set up	5	**175**
78	Inverter	Inverter I/O - Pin 29	CAN Open L	Open	CAN Bus inoperable - Motor System disabled - decrease performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault during HIL Set up	5	**175**
79	Inverter	Inverter I/O - Pin 30	CAN Open H	Short To Ground	CAN Bus inoperable - Motor System disabled - decrease performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault during HIL Set up	5	**175**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
80	Inverter	Inverter I/O - Pin 30	CAN Open H	Short To Logic	CAN Bus inoperable - Motor System disabled - decrease performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault during HIL Set up	5	**175**
81	Inverter	Inverter I/O - Pin 30	CAN Open H	Open	CAN Bus inoperable - Motor System disabled - decrease performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault during HIL Set up	5	**175**
82	Inverter	Inverter I/O - Pin 35	Unit_Enable	Short To Ground	Motor System Disabled - performance decreased	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault during HIL Set up	5	**175**
83	Inverter	Inverter I/O - Pin 35	Unit_Enable	Open	Motor System Disabled - performance decreased	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault during HIL Set up	5	**175**
84	Inverter	Inverter I/O - Pin 36	Logic Supply	Short To Ground	Inverter loses power - motor system disabled	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	5	**175**
85	Inverter	Inverter I/O - Pin 36	Logic Supply	Open	Inverter loses power - motor system disabled	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	5	**175**
86	Inverter	Inverter I/O - Pin 38	Logic Supply - GND	Short To Logic	Inverter loses power - motor system disabled	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	5	**175**
87	Inverter	Inverter I/O - Pin 38	Logic Supply - GND	Open	Inverter loses power - motor system disabled	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	5	**175**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
88	Inverter	Inverter I/O - Pin 39	Logic Supply	Short To Ground	Inverter loses power - motor system disabled	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	5	**175**
89	Inverter	Inverter I/O - Pin 39	Logic Supply	Open	Inverter loses power - motor system disabled	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	5	**175**
90	Inverter	Start Up	The inverter shall be verified by the HVSC that it is not transmitting faults. If the inverter is transmitting faults they must be identified, resolved, and cleared before proceeding	HVSC does not verify that the inverter is transmitting faults	Motor System Disabled	7	Improper code in the HVSC	4	SIL and HIL testing	HVSC shall verify that the inverter is sending faults	6	**168**
91	Inverter	Communication Output	The inverter shall send a diagnostic message any time a fault is triggered	A fault does not trigger within the system	Permanent Damage of Motor System	8	Faulty wiring between Inverter and HVSC	2	Inspection from additional CSMS Member	None - InMotion defined and programmed function	10	**160**
92	Inverter	Constraint	The motor shall not exceed the torque rate limit	The motor exceeds the torque rate limit	Unintended acceleration	10	Improper code in the HVSC	4	SIL and HIL testing	HVSC shall send a signal if the motor exceeds torque rate limit	4	**160**
93	Inverter	Constraint	The motor shall not exceed the speed rate limit	The motor exceeds the speed rate limit	Unintended acceleration	10	Improper code in the HVSC	4	SIL and HIL testing	HVSC shall verify that the inverter is receiving the speed rate limit	4	**160**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
94	Inverter	Constraint	The motor shall operate in torque mode	The motor does not operate in torque mode	Unknown Torque Produced	10	Improper code in the HVSC	4	SIL and HIL testing	HVSC receives status signal when speed mode is entered	4	**160**
95	Inverter	Communication Output	The inverter shall send the operation time output	Inverter does not send operation time output	Undesired motor torque	10	Overloaded electric torque bus	2	Place electric torque on separate bus	HVSC shall monitor bus loading to determine if signals are being lost. DriveTool can be used during vehicle testing	8	**160**
96	Inverter	Communication Output	The inverter shall send the torque reference manager message	Inverter does not send the torque reference manager message	Unknown actual torque produced by motor	10	Overloaded electric torque bus	2	Place electric torque on separate bus	HVSC shall monitor bus loading to determine if signals are being lost	8	**160**
97	Inverter	Communication Output	The inverter shall send the torque current limit message	Inverter does not send the torque current limit message	Too much torque produced by motor	10	Overloaded electric torque bus	2	Place electric torque on separate bus	HVSC shall monitor bus loading to determine if signals are being lost	8	**160**
98	Inverter	Communication Output	The inverter shall send the torque current limit message	Inverter does not send the torque current limit message	Too little torque produced by motor	10	Overloaded electric torque bus	2	Place electric torque on separate bus	HVSC shall monitor bus loading to determine if signals are being lost	8	**160**
99	Inverter	Communication Output	The inverter shall send the application status message	Inverter does not send application status message	Unknown status of Motor System	5	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HVSC shall verify communication with the inverter	6	**150**
100	Inverter	Communication Output	The inverter shall send the application Status word (Sw) information	Inverter does not send application Sw information	Unknown status of Motor System	5	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HVSC shall verify communication with the inverter	6	**150**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
101	Inverter	Communication Output	The inverter shall send the application setup parameters	Inverter does not send the application setup parameters	Motor System unable to be used	5	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HVSC shall verify communication with the inverter	6	**150**
102	Inverter	Communication Output	The inverter shall send DC bus message	Inverter does not send DC bus voltage	Motor System unable to be used	5	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HVSC shall verify communication with the inverter	6	**150**
103	Inverter	Communication Output	The inverter shall send the motor measurements message	Inverter does not send the motor measurements message	Unknown status of motor	5	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HVSC shall verify communication with the inverter	6	**150**
104	Inverter	Communication Output	The inverter shall send a diagnostic message any time a fault is triggered	Inverter does not send diagnostic message	Unknown status of inverter	5	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HVSC shall verify communication with the inverter	6	**150**
105	Inverter	Communication Output	The inverter shall send a diagnostic message any time a fault is triggered	Inverter does not send diagnostic message	Unknown status of motor	5	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HVSC shall verify communication with the inverter	6	**150**
106	Inverter	Start Up	The inverter shall be verified by the HVSC that it is not transmitting faults. If the inverter is transmitting faults they must be identified, resolved, and	HVSC does not verify that the inverter is transmitting faults	Inverter overheats	5	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HVSC shall verify communication with the inverter	6	**150**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
			cleared before proceeding									
107	Inverter	Start Up	The inverter shall be verified by the HVSC that it is not transmitting faults. If the inverter is transmitting faults they must be identified, resolved, and cleared before proceeding	HVSC does not verify that the inverter is transmitting faults	Motor overheats	5	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HVSC shall verify communication with the inverter	6	**150**
108	Inverter	Start Up	The inverter CAN message communication shall be verified by the HVSC	Communication is not verified by the HVSC	Unknown if the Inverter is receiving messages from the HVSC	6	Inverter not receiving messages over CAN	4	SIL and HIL testing	HVSC shall send a signal to the driver establishing that the inverter is not started	6	**144**
109	Inverter	Communication Output	The inverter shall send the DC power limit	Inverter does not send the DC power limit	Inverter operates outside of safe operation range	9	Overloaded electric torque bus	2	Place electric torque on separate bus	HVSC shall monitor bus loading to determine if signals are being lost	8	**144**
110	Inverter	Communication Output	The inverter shall send the DC power limit	Inverter does not send the DC power limit	Motor operates outside of safe operation range	9	Overloaded electric torque bus	2	Place electric torque on separate bus	HVSC shall monitor bus loading to determine if signals are being lost	8	**144**
111	Inverter	Communication Output	The inverter shall send a diagnostic message any time a fault is triggered	A fault does not trigger within the system	Inverter overheats	7	Faulty wiring between Inverter and HVSC	2	Inspection from additional CSMS Member	None - InMotion defined and programmed function	10	**140**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
112	Inverter	Communication Output	The inverter shall send a diagnostic message any time a fault is triggered	A fault does not trigger within the system	Motor overheats	7	Faulty wiring between Inverter and HVSC	2	Inspection from additional CSMS Member	None - InMotion defined and programmed function	10	**140**
113	Inverter	Constraint	The motor shall not exceed the maximum rated temperature	Motor exceeds maximum rate temperature	Motor overheats	7	Improper code in the Inverter	5	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	The inverter sends signal to HVSC	4	**140**
114	Inverter	Communication Input	The inverter shall receive a hazardous voltage interlock voltage input for diagnostic of motor system HVIL	Inverter does not receive voltage for diagnostic of motor	Inverter overheats	7	Faulty wiring between ESS and Inverter	5	Inspection from additional CSMS Member	HVSC shall verify that the Inverter can perform diagnostics	4	**140**
115	Inverter	Communication Input	The inverter shall receive a hazardous voltage interlock voltage input for diagnostic of motor system HVIL	Inverter does not receive voltage for diagnostic of motor	Motor overheats	7	Faulty wiring between ESS and Inverter	5	Inspection from additional CSMS Member	HVSC shall verify that the Inverter can perform diagnostics	4	**140**
116	Inverter	Communication Input	The inverter shall receive a hazardous voltage interlock voltage input for diagnostic of motor system HVIL	Inverter does not receive voltage for diagnostic of motor	Motor System Disabled	7	Faulty wiring between ESS and Inverter	5	Inspection from additional CSMS Member	HVSC shall verify that the Inverter can perform diagnostics	4	**140**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
117	Inverter	Communication Output	The inverter shall send the motor and inverter temperature	Inverter does not send the motor temperature	Motor overheats	7	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HVSC shall verify communication with the inverter	4	**140**
118	Inverter	Communication Output	The inverter shall send the motor and inverter temperature	Inverter does not send inverter temperature	Inverter overheats	7	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HVSC shall verify communication with the inverter	4	**140**
119	Inverter	Communication Output	The inverter shall send the power stage temperature	Inverter does not send the power stage temperature	Inverter overheats	7	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HVSC shall verify communication with the inverter	4	**140**
120	Inverter	Communication Output	The inverter shall send the PCB temperature	Inverter does not send the PCB temperature	Inverter overheats	7	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HVSC shall verify communication with the inverter	4	**140**
121	Inverter	Inverter I/O - Pin 32	~Safe Torque Off (High)	Short To Ground	Motor System Disabled - performance decreased	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	4	**140**
122	Inverter	Inverter I/O - Pin 32	~Safe Torque Off (High)	Open	Motor System Disabled - performance decreased	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	4	**140**
123	Inverter	Inverter I/O - Pin 33	Safe Torque Off (Low)	Short To Logic	Motor System Disabled - performance decreased	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	4	**140**
124	Inverter	Inverter I/O - Pin 33	Safe Torque Off (Low)	Open	Motor System Disabled - performance decreased	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	4	**140**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
125	Inverter	Start Up	The inverter shall be verified by the HVSC that it is not transmitting faults. If the inverter is transmitting faults they must be identified, resolved, and cleared before proceeding	Inverter does not transmit faults	Motor System Disabled	7	Overloaded electric torque bus	2	Place electric torque on separate bus	None - InMotion defined and programmed function	10	**140**
126	Stator	Wound Stator Assembly	Connects Incoming Current (Defines /Provides connectivity)	does not define/ provide connectivity	Does not meet customer req'ts, Direction of Rotation problems, Inadequate spacing for heat and assembly, cannot make final connections	7	Incorrect connection procedure specified	6	crimping information called out on drawing	POC builds, prototype and preseries builds	3	**126**
127	Stator	Wound Stator Assembly	Connects Incoming Current (Defines /Provides connectivity)	does not define/ provide connectivity	Does not meet customer req'ts, Direction of Rotation problems, Inadequate spacing for heat and assembly, cannot make final connections	7	Incorrect start position defined for phase 1 start	6	crimping information called out on drawing	POC builds, prototype and preseries builds	3	**126**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
128	Motor Mount	Floorplan to Motor Connection	Handle Reaction Torque/ Locate Motor	Fails to handle reaction torque	Mounting Structure Yield/Fracture	10	Shock Loads	6	FEA	FEA	2	**120**
129	Inverter	Start Up	The inverter shall be verified by the HVSC that it is not transmitting faults. If the inverter is transmitting faults they must be identified, resolved, and cleared before proceeding	HVSC does not verify that the inverter is transmitting faults	Inverter overheats	5	Improper code in the HVSC	4	SIL and HIL testing	HVSC shall verify that the inverter is sending faults	6	**120**
130	Inverter	Start Up	The inverter shall be verified by the HVSC that it is not transmitting faults. If the inverter is transmitting faults they must be identified, resolved, and cleared before proceeding	HVSC does not verify that the inverter is transmitting faults	Motor overheats	5	Improper code in the HVSC	4	SIL and HIL testing	HVSC shall verify that the inverter is sending faults	6	**120**
131	Inverter	Start Up	The inverter shall be enabled through a CAN command message	The inverter is not enabled by the HVSC	Inverter is not enabled	5	Improper code in the HVSC	4	SIL and HIL testing	HVSC shall send a signal to the driver if the inverter is not enabled	6	**120**
132	Inverter	Communication Output	The inverter shall send the	Inverter does not send the feedback sensor message	Unknown torque produced	10	Overloaded electric torque bus	2	Place electric torque on separate bus	HVSC shall monitor bus loading to	6	**120**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
			feedback sensor message							determine if signals are being lost		
133	Inverter	Emergency Response	The inverter shall receive a zero torque command from a HVSC CAN message	The inverter does not receive a zero torque command from the HVSC	Unintended acceleration	10	Overloaded electric torque bus	2	Place electric torque on separate bus	HIL Testing	6	**120**
134	Motor Assembly	Bearings	Support Motor Weight	Crushed bearing	Bearing Failure - Vehicle Inoperable	6	unexpected shock load	2	No prevention method	No detection method	10	**120**
135	Inverter	Communication Input	The inverter shall receive a torque command from the HVSC	Inverter does not receive the torque command from the HVSC	Loss of motor torque	7	Improper code in the HVSC	4	Validation through SIL/HIL	HVSC shall send a signal to the driver if the inverter is not enabled	4	**112**
136	Stator	Wound Stator Assembly	Prevent voltage breakdown (insulation system)	does not insulate motor windings	shorts, grounds	8	incorrect definition of insulation position	7	Define axial location of phase separator and slot liner	prototype and preseries builds	2	**112**
137	Stator	Wound Stator Assembly	Prevent voltage breakdown (insulation system)	does not insulate motor windings	shorts, grounds	8	incorrect clearance between end turns and end bells	7	UL and customer specifications	POC builds, prototype and preseries builds	2	**112**
138	Inverter	Communication Input	The inverter shall receive a hazardous voltage interlock voltage input for diagnostic of motor system HVIL	Inverter does not receive voltage for diagnostic of motor	Inverter overheats	7	Improper code in the HVSC	4	SIL and HIL testing	HVSC shall verify that the inverter is getting the correct voltage	4	**112**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
139	Inverter	Communication Input	The inverter shall receive a hazardous voltage interlock voltage input for diagnostic of motor system HVIL	Inverter does not receive voltage for diagnostic of motor	Motor overheats	7	Improper code in the HVSC	4	SIL and HIL testing	HVSC shall verify that the inverter is getting the correct voltage	4	**112**
140	Inverter	Communication Input	The inverter shall receive a hazardous voltage interlock voltage input for diagnostic of motor system HVIL	Inverter does not receive voltage for diagnostic of motor	Motor System Disabled	7	Improper code in the HVSC	4	SIL and HIL testing	HVSC shall verify that the inverter is getting the correct voltage	4	**112**
141	Inverter	Constraint	The motor shall decay from peak torque to continuous torque based on thermal considerations	The motor does not decay from peak to continuous torque based on temperature	Motor overheats	7	Improper code in the HVSC	4	SIL and HIL testing	HVSC shall test for temperature in SIL	4	**112**
142	Inverter	Constraint	The inverter shall not exceed the maximum rated temperature	Inverter exceeds maximum rated temperature	Inverter overheats	7	Improper code in the HVSC	4	SIL and HIL testing	HVSC shall continuously monitor inverter temperature	4	**112**
143	Inverter	Communication Input	The inverter shall receive a torque command from the HVSC	Inverter does not receive the torque command from the HVSC	Loss of motor torque	7	Overloaded electric torque bus	2	Motor System is on isolated CAN Bus	HVSC shall monitor bus loading to determine if signals are being lost	8	**112**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
144	Inverter	Communication Output	The inverter shall send the motor and inverter temperature	Inverter does not send inverter temperature	Inverter overheats	7	Overloaded electric torque bus	2	Place electric torque on separate bus	HVSC shall monitor bus loading to determine if signals are being lost	8	**112**
145	Inverter	Communication Output	The inverter shall send the power stage temperature	Inverter does not send the power stage temperature	Inverter overheats	7	Overloaded electric torque bus	2	Place electric torque on separate bus	HVSC shall monitor bus loading to determine if signals are being lost	8	**112**
146	Inverter	Communication Output	The inverter shall send the PCB temperature	Inverter does not send the PCB temperature	Inverter overheats	7	Overloaded electric torque bus	2	Place electric torque on separate bus	HVSC shall monitor bus loading to determine if signals are being lost	8	**112**
147	Inverter	Communication Output	The inverter shall send the motor and inverter temperature	Inverter does not send the motor temperature	Motor overheats	7	Overloaded electric torque bus	2	Place electric torque on separate bus	HVSC shall monitor bus loading to determine if signals are being lost	8	**112**
148	Inverter	Start Up	The inverter shall be verified by the HVSC that it is not transmitting faults. If the inverter is transmitting faults they must be identified, resolved, and cleared before proceeding	HVSC does not verify that the inverter is transmitting faults	Motor System Disabled	7	Overloaded electric torque bus	2	Place electric torque on separate bus	HVSC shall monitor bus loading to determine if signals are being lost	8	**112**
149	Inverter	Start Up	The inverter shall be verified by the HVSC that it is not	Faults are not resolved	Motor System Disabled	7	Overloaded electric torque bus	2	Place electric torque on separate bus	HVSC Shall verify that the inverter is not sending faults	8	**112**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
			transmitting faults. If the inverter is transmitting faults they must be identified, resolved, and cleared before proceeding									
150	Stator	Slot Insulation	Positions insulator & maintains proper creapage & clearance	Does not maintain proper creapage & clearance	Winding short - Motor fails - shock hazard	9	Cuff dimension not correct.	6	material spec & supplier data	Poc builds, prototype and preseries builds	2	**108**
151	Stator	Wound Stator Assembly	identifies part	Part not identified	use of wrong part	7	Note does not clearly tell operator what to do	5	Have note	POC builds, prototype and preseries builds	3	**105**
152	Rotor	Rotor Core	Transmit Heat	rotor over heats	loss torque and performance	7	incorrect dimensions on fin design	3	FEA analysis	Prototype build and thermal testing	5	**105**
153	Inverter	Communication Input	The inverter shall receive the motor speed from the resolver sensor	Inverter does not receive motor speed	Unknown actual torque produced by motor	10	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	Inverter shall verify that the resolver is transmitting motor speed	10	**100**
154	Inverter	Communication Input	The inverter shall receive the motor speed from the resolver sensor	Inverter does not receive the motor speed from the resolver	Unknown actual torque produced by motor	10	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	Inverter shall monitor motor speed	10	**100**
155	Inverter	Constraint	The inverter shall continuously monitor the current and	Inverter does not continuously monitor the current going to the motor	Unknown Torque Produced	10	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	None - InMotion defined and programmed function	10	**100**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
			voltage going to the motor									
156	Inverter	Constraint	The inverter shall continuously monitor the current and voltage going to the motor	Inverter does not continuously monitor the voltage going to the motor	Unknown Torque Produced	10	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	None - InMotion defined and programmed function	10	**100**
157	Inverter	Communication Input	The inverter shall receive the motor speed from the resolver sensor	Inverter does not receive the motor speed from the resolver	Unknown actual torque produced by motor	10	Faulty resolver wiring	1	None	Inverter shall verify that the resolver is transmitting motor speed	10	**100**
158	Inverter	Start Up	The inverter shall be enabled by an HVSC CAN command message	Inverter is not enabled by the HVSC for start up	Inverter is not enabled	5	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HVSC shall send a signal to the driver if the inverter is not enabled	4	**100**
159	Inverter	Start Up	The inverter shall be enabled through a CAN command message	The inverter is not enabled by the HVSC	Inverter is not enabled	5	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HVSC shall verify communication with the inverter	4	**100**
160	Inverter	Communication Input	The inverter shall send a PDO timeout message	Inverter does not send a PDO timeout message	Inverter overheats	5	Overloaded electric torque bus	2	Place electric torque on separate bus	None - InMotion defined and programmed function	10	**100**
161	Inverter	Communication Input	The inverter shall send a PDO timeout message	Inverter does not send a PDO timeout message	Motor overheats	5	Overloaded electric torque bus	2	Place electric torque on separate bus	None - InMotion defined and programmed function	10	**100**
162	Motorshaft	Motorshaft/spline connection	Provides Concentric Connection Between Center Bearing and	non-concentric connection	Drivetrain misalignment - loss of performance & comfort. Early	8	Improper tolerance and motor assembly constraints	3	assembly method well defined	prototype	4	**96**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
			Rear differential		unplanned maintenance and high probability of driveline failure - vehicle inoperable							
163	Inverter	Start Up	The inverter CAN message communication shall be verified by the HVSC	Communication is not verified by the HVSC	Unknown if the Inverter is receiving messages from the HVSC	6	Overloaded Electric Torque Bus	2	Place electric torque on separate bus	HVSC shall monitor bus loading to determine if signals are being lost	8	**96**
164	Rotor	Rotor Core	Carry Current	resistance too high	excessive heating and loss of performance	7	porosity in cast material	3	Al casting inspection and pervious experience	Prototype build	4	**84**
165	Motor Assembly	Bearings	Support Motor Weight	Bearings Seize	Equipment Shutdown	8	Shaft Misalignment	2	assembly method well defined	visual inspection, prototype	5	**80**
166	Inverter	Communication Output	The inverter shall send the operation time output	Inverter does not send operation time output	Undesired motor torque	10	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC shall monitor bus loading to determine if signals are being lost. DriveTool can be used during vehicle testing	8	**80**
167	Inverter	Communication Output	The inverter shall send a diagnostic message any time a fault is triggered	A fault does not trigger within the system	Permanent Damage of Motor System	8	Improper code in the HVSC	1	SIL and HIL testing	None - InMotion defined and programmed function	10	**80**
168	Inverter	Constraint	The inverter shall operate above a	Inverter does not operate above the minimum voltage	Inverter does not operate as expected	5	Improper code in the HVSC	4	SIL and HIL testing	HVSC shall send a signal to the driver if the inverter is not enabled	4	**80**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
			minimum voltage									
169	Inverter	Start Up	The inverter shall be enabled by an HVSC CAN command message	Inverter is not enabled by the HVSC for start up	Inverter is not enabled	5	Improper code in the HVSC	4	SIL and HIL testing	HVSC shall send a signal to the driver if the inverter is not enabled	4	**80**
170	Inverter	Communication Output	The inverter shall send the application status message	Inverter does not send application status message	Unknown status of Motor System	5	Overloaded electric torque bus	2	Place electric torque on separate bus	HVSC shall monitor bus loading to determine if signals are being lost. DriveTool can be used during vehicle testing	8	**80**
171	Inverter	Communication Output	The inverter shall send the motor measurements message	Inverter does not send the motor measurements message	Unknown status of motor	5	Overloaded electric torque bus	2	Place electric torque on separate bus	HVSC shall monitor bus loading to determine if signals are being lost	8	**80**
172	Inverter	Communication Output	The inverter shall send a diagnostic message any time a fault is triggered	Inverter does not send diagnostic message	Unknown status of inverter	5	Overloaded electric torque bus	2	Place electric torque on separate bus	HVSC shall monitor bus loading to determine if signals are being lost	8	**80**
173	Inverter	Communication Output	The inverter shall send a diagnostic message any time a fault is triggered	Inverter does not send diagnostic message	Unknown status of motor	5	Overloaded electric torque bus	2	Place electric torque on separate bus	HVSC shall monitor bus loading to determine if signals are being lost	8	**80**
174	Inverter	Start Up	The inverter shall be verified by the HVSC that it is not transmitting	HVSC does not verify that the inverter is transmitting faults	Inverter overheats	5	Overloaded electric torque bus	2	Place electric torque on separate bus	HVSC shall monitor bus loading to determine if signals are being lost	8	**80**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
			faults. If the inverter is transmitting faults they must be identified, resolved, and cleared before proceeding									
175	Inverter	Start Up	The inverter shall be verified by the HVSC that it is not transmitting faults. If the inverter is transmitting faults they must be identified, resolved, and cleared before proceeding	HVSC does not verify that the inverter is transmitting faults	Motor overheats	5	Overloaded electric torque bus	2	Place electric torque on separate bus	HVSC shall monitor bus loading to determine if signals are being lost	8	**80**
176	Inverter	Inverter I/O - Pin 35	Unit_Enable	Short To Logic	Inverter cannot enter sleep mode - increased parasitic losses - drain 12V	3	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault during HIL Set up	5	**75**
177	Rotor	Rotor Laminations	Permit Rotation (Provides consistent air gap)	Incorrect outer features	Air gap incorrect - rubbing - rotor lock up / cogging/ low torque	8	OD shape feature incorrect/ High cogging torque	3	Analysis	POC's and prototypes	3	**72**
178	Rotor	Rotor Laminations	Permit Rotation (Provides consistent air gap)	Incorrect outer features	Air gap incorrect - rubbing - rotor lock up / cogging/ low torque	8	Airgap too large/ low torque	3	Analysis	POC's and prototypes	3	**72**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
179	Rotor	Rotor Laminations	Locates bars	Incorrect bar location	Low torque	8	Incorrect bar count and slot width.	3	Analysis	POC's and prototypes	3	**72**
180	Stator	Slot Insulation	Protects wire during winding	Wire damaged during manufacture	Winding short - Motor fails - shock hazard	9	Incorrect dimensions	4	stator lam & component layout & proto build	Poc builds, prototype and preseries builds	2	**72**
181	Stator	Slot Phase Separator	Insulate phases within slot	Fails to insulate	Winding short -	9	Incorrect dimensions	4	stator lam & component layout	prototype build	2	**72**
182	Stator	Top Wedge	Prevent wires entering stator ID during manufacture	Wire damaged during manufacture	Scrap stator	9	Incorrect dimensions	4	stator lam & slot wedge layout	prototype build	2	**72**
183	Stator	Top Wedge	Insulate wires from lamination teeth	Wire shorts to lamination	Scrap stator	9	Incorrect dimensions	4	stator lam & slot wedge layout & proto build	prototype build, high pot test, visual	2	**72**
184	Stator	Top Wedge	Insulate wires from lamination teeth	Wire shorts to lamination	Ground fault - shock hazard	9	High slot fill	4	stator lam & slot wedge layout	prototype build, high pot test, visual	2	**72**
185	Motor Assembly	Bearings	Support Motor Weight	Bearings Seize	Repair shaft (expensive)	7	Shaft Misalignment	2	assembly method well defined	visual inspection, prototype	5	**70**
186	Inverter	Communication Input	The inverter shall receive EEPROM parameters	Inverter does not receive EEPROM parameters	Motor used outside of correct operation range	7	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	None - InMotion defined and programmed function	10	**70**
187	Inverter	Communication Output	The inverter shall send a diagnostic message any time a fault is triggered	A fault does not trigger within the system	Inverter overheats	7	Improper code in the HVSC	1	SIL and HIL testing	None - InMotion defined and programmed function	10	**70**
188	Inverter	Communication Output	The inverter shall send a diagnostic message any	A fault does not trigger within the system	Motor overheats	7	Improper code in the HVSC	1	SIL and HIL testing	None - InMotion defined and programmed function	10	**70**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
			time a fault is triggered									
189	Inverter	Constraint	The inverter shall continuously monitor the power stage temperature and the motor temperature	Inverter does not continuously monitor the power stage temperature	Inverter overheats	7	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	None - InMotion defined and programmed function	10	**70**
190	Inverter	Constraint	The inverter shall continuously monitor the power stage temperature and the motor temperature	Inverter does not continuously monitor the motor temperature	Motor overheats	7	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	None - InMotion defined and programmed function	10	**70**
191	Inverter	Start Up	The inverter shall be verified by the HVSC that it is not transmitting faults. If the inverter is transmitting faults they must be identified, resolved, and cleared before proceeding	Inverter does not transmit faults	Motor System Disabled	7	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	None - InMotion defined and programmed function	10	**70**
192	Rotor	Rotor Core	Clearance for shrink fit over hub	Incorrect shrink fit	loss of torque, motor fails	8	Dimensioned incorrectly	2	Tolerance stack up study between hub and lam stack	Prototype build	4	**64**
193	Rotor	Rotor Core	Transmit Torque (shrink fit)	Does not shrink fit properly	loss of torque, motor fails	8	Dimensioned incorrectly	2	Tolerance stack up study between hub and lam stack	Prototype build	4	**64**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
194	Rotor	Rotor Laminations	Transmit torque to hub	does not transmit torque	loss of torque, motor fails	8	Dimensioned incorrectly	2	Tolerance stack up study between hub and lam stack	Prototype build	4	**64**
195	Inverter	Constraint	The inverter shall remain above a minimum temperature	Inverter falls below the minimum temperature	Inverter operates outside of safe operation range	4	Improper code in the HVSC	4	SIL and HIL testing	HVSC shall send a signal to the driver if the inverter is not enabled	4	**64**
196	Stator	Wound Stator Assembly	Reacts to Electromagnetic Torque	fails to react magnetic torque	Slippage of laminations in housing. Overheating, Possible shutdown, reduced ride quality.	7	Incorrect shrink fit specified	3	analysis of shrink fit completed over operating range, previous Bus motor designed by Customer	POC builds, prototype and preseries builds	3	**63**
197	Stator	Wound Stator Assembly	Defines Magnet Wire Turns, EM performance, location and definition	Incorrect Winding Design	Inadequate torque, Excessive Heating, Circulating currents, reduced ride quality,	7	KWD improperly defined	3	Analysis	POC's and prototype builds	3	**63**
198	Motor Mount	Floorplan to Motor Connection	Handle Reaction Torque/ Locate Motor	Fails to handle reaction torque	Mounting Structure Yield/Fracture	10	Fatigue Failure	3	FEA - Dynamic Loading	FEA	2	**60**
199	Motorshaft	Motorshaft/spline connection	Transmit requested Torque	Fails to Transmit required torque	Loss of primary function, vehicle inoperable	10	Improper Material Processing Specified	3	FEA	Fea	2	**60**
200	Inverter	Communication Output	The inverter shall send the feedback sensor message	Inverter does not send the feedback sensor message	Unknown torque produced	10	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test	HVSC shall verify communication with the inverter	6	**60**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
									Inverter prior to HEVT Testing			
201	Inverter	Communication Output	The inverter shall send the torque reference manager message	Inverter does not send the torque reference manager message	Unknown actual torque produced by motor	10	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC shall verify communication with the inverter	6	**60**
202	Inverter	Communication Output	The inverter shall send the torque current limit message	Inverter does not send the torque current limit message	Too much torque produced by motor	10	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC shall verify communication with the inverter	6	**60**
203	Inverter	Communication Output	The inverter shall send the torque current limit message	Inverter does not send the torque current limit message	Too little torque produced by motor	10	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC shall verify communication with the inverter	6	**60**
204	Inverter	Communication Output	The inverter shall send the application Status word (Sw) information	Inverter does not send application Sw information	Unknown status of Motor System	5	Overloaded electric torque bus	2	Place electric torque on separate bus	HVSC shall monitor bus loading to determine if signals are being lost	6	**60**
205	Inverter	Communication Output	The inverter shall send the application setup parameters	Inverter does not send the application setup parameters	Motor System unable to be used	5	Overloaded electric torque bus	2	Place electric torque on separate bus	HVSC shall monitor bus loading to determine if signals are being lost	6	**60**
206	Inverter	Communication Output	The inverter shall send DC bus message	Inverter does not send DC bus voltage	Motor System unable to be used	5	Overloaded electric torque bus	2	Place electric torque on separate bus	HVSC shall monitor bus loading to determine if signals are being lost	6	**60**
207	Rotor	Rotor Laminations	Protected from corrosion during shipment	Laminations corroded	Noise/vibration	7	Corrosions protection not specified	2	Called on drawing, previous experience	Previous laminations	4	**56**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
208	Stator	Stator Core Bonded & Machined	Maintain rigid structure to support winding	Structure not rigid	core breaks before vpi is set; scrap core	7	improper bond material	4	Called out on drawing and used in similar applications	POC builds, prototype and preseries builds, Assembly not possible	2	**56**
209	Stator	Wound Stator Assembly	Carry current of motor into windings (length, size, orientation)	Incorrect definitions for magnet wire leads	cannot connect motor, lead wire insulation failure	7	incorrect wire position	4	Analysis of terminal connections, tooling creation	Poc builds, prototype and preseries builds	2	**56**
210	Motor Wires	3-Phase Lines	Transmit AC	Fails to Transmit required current	Component Shutdown	8	Wear and Rubbing	1	assembly method well defined	Visual Inspection and Measurement	7	**56**
211	Motor Assembly	Bearings	Support Motor Weight	Bearings Seize	Overload and overheat motor	7	Shaft Misalignment	2	assembly method well defined	visual inspection, grinding, shake	4	**56**
212	Inverter	Constraint	The motor shall not exceed the maximum rated temperature	Motor exceeds maximum rate temperature	Motor overheats	7	Faulty wiring between Inverter and HVSC	2	Inspection from additional CSMS Member	HVSC shall verify communication with the inverter	4	**56**
213	Inverter	Constraint	The inverter shall not exceed the maximum rated temperature	Inverter exceeds maximum rated temperature	Inverter overheats	7	Faulty temperature sensor	2	Fault Testing prior to component bench testing	HVSC shall continuously monitor inverter temperature	4	**56**
214	Rotor	Rotor Laminations	Conducts Electromagnetic Flux	Does not conduct EM Flux	Low efficiency & low torque	6	Incorrect material defined	3	Analysis	POC's and prototypes	3	**54**
215	Rotor	Rotor Laminations	Conducts Electromagnetic Flux	Does not conduct EM Flux	Low efficiency & low torque	6	Not enough back iron defined	3	Analysis	POC's and prototypes	3	**54**
216	Rotor	Rotor Laminations	Conducts Electromagnetic Flux	Material not properly annealed	Low efficiency & low torque	6	Incorrect alleal called out	3	Analysis and previous experience	POC's and prototypes	3	**54**
217	Rotor	Rotor Laminations	Conducts Electromagnetic Flux	Incorrect bar hole shape	Low efficiency & low torque	6	bar shape incorrect	3	Analysis	POC's and prototypes	3	**54**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
218	Stator	Slot Insulation	insulates magnet wire from core	Fails to insulate	Winding short - Motor fails - shock hazard	9	Incorrect thermal, electrical and mechanical properties	3	material spec & supplier data	Poc builds, prototype and preseries builds	2	**54**
219	Stator	Slot Insulation	insulates magnet wire from core	Fails to insulate	Winding short - Motor fails - shock hazard	9	High voltage stress	3	Voltage stress calculations	Poc builds, prototype and preseries builds	2	**54**
220	Resolver	Resolver	Measure Motor Position	Resolver Misalignment	Slip - Inaccurate Torque Response	7	Improperly Calibrated at assembly	1	previous experience, digital measurements	prototype/analysis	7	**49**
221	Rotor	Rotor Core	Provide mechanical retention of AL bars	bars extrude into airgap at high speed	Lock up airgap and motor fails	8	Slot shape dimensioned incorrectly	3	Design review, SPEED, FEA analysis	Prototype build	2	**48**
222	Rotor	Rotor Core	Set the lamination stack length	Incorrect length	low torque and performance	8	incorrectly dimensioned	3	Design review, SPEED, FEA analysis	Prototype build	2	**48**
223	Rotor	Rotor Laminations	Provide mechanical retention of AL bars	bars extrude into airgap at high speed	Lock up airgap and motor fails	8	Slot shape dimensioned incorrectly	3	Design review, SPEED, FEA analysis	Prototype build	2	**48**
224	Rotor	Rotor Laminations	Permit Rotation (Provides consistent air gap)	Incorrect outer features	Air gap incorrect - rubbing - rotor lock up / cogging/ low torque	8	Airgap too small/ Part rubs	2	Called on drawing, previous experience	POC's and prototypes	3	**48**
225	Stator	Stator Lamination	Directs EM Flux	Does Not Direct Flux per Design Intent	Fail to meet minimum torque; excessive heat; high torque ripple; reduced	8	Tooth Geometry Incorrect	2	Analysis, FEA, Analytical	POC's and Prototypes	3	**48**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
					motor performance							
226	Stator	Stator Lamination	Directs EM Flux	Does Not Direct Flux per Design Intent	Fail to meet minimum torque; excessive heat; high torque ripple; reduced motor performance	8	Insufficient Back Iron	2	Analysis, FEA, Analytical	POC's and Prototypes	3	**48**
227	Stator	Stator Lamination	Directs EM Flux	Does Not Direct Flux per Design Intent	Fail to meet minimum torque; excessive heat; high torque ripple; reduced motor performance	8	Incorrect Material Specification	2	Analysis, FEA, Analytical	POC's and Prototypes	3	**48**
228	Stator	Stator Lamination	Positions Windings	Windings not in correct position	Fail to meet minimum torque; excessive heat; high torque ripple; reduced motor performance	8	Incorrect Slot Dimensions	2	Analysis, FEA, Analytical	POC's and Prototypes	3	**48**
229	Stator	Stator Lamination	Positions Windings	Cannot hold required wire	Cannot assemble	8	Incorrect Slot Dimensions	2	Analysis,Analyitical	POC's and Prototypes	3	**48**
230	Stator	Wound Stator Assembly	Conduct/ Dissipate Heat	Motor overheats	Shorten motor life, bus shut down	8	Insufficient conductive surface area	3	axial tolerance study, thermal modeling, FEA	Poc builds, prototype and preseries builds	2	**48**
231	Stator	Wound Stator Assembly	Prevent voltage breakdown (insulation system)	does not insulate motor windings	shorts, grounds	8	incorrect VPI coverage specified	3	Customer specifications	Poc builds, prototype and preseries builds	2	**48**
232	Motor Assembly	Bearings	Support Motor Weight	Bearing Slip	Vibration	4	improper assembly	2	quality control	visual inspection	6	**48**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
233	Motorshaft	Shaft - Rotor Connection	Transmit requested Torque	Fails to Transmit requested Torque	Equipment Shutdown	8	Improper Installation - Improper design tolerances	1	assembly method well defined	prototype	6	**48**
234	Motorshaft	Shaft - Rotor Connection	Transmit requested Torque	Fails to Transmit requested Torque	Equipment Shutdown	8	Corrosion - Improper surface finish	1	assembly method well defined	prototype	6	**48**
235	Rotor	Rotor Core	maintains end rings at high speed	end ring burst at high speed	machine fails	8	incorrect material for size of rotor	1	FEA Analysis with Inconel band fails.	Prototype build and special rotor temp cycle test	6	**48**
236	Inverter	Start Up	The inverter shall be verified by the HVSC that it is not transmitting faults. If the inverter is transmitting faults they must be identified, resolved, and cleared before proceeding	Faults are not resolved	Motor System Disabled	7	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC Shall verify that the inverter is not sending faults	6	**42**
237	Stator	Stator Core Bonded & Machined	Controls Air Gap			7	Outer diameter not concentric	3	dimensions called out on drawings	POC builds, prototype and preseries builds, Assembly not possible	2	**42**
238	Motorshaft	Motorshaft/spline connection	Support Rotor Weight	does not rotor support weight	motorshaft misalignment - loss of performance & comfort	7	Improper Material Specified	3	Utilized OEM Design, InMotion prior experience.	FEA	2	**42**
239	Stator	Stator Core Bonded & Machined	Controls Air Gap	Air gap too large	reduced performance, increased	7	Bore diameter too large	3	dimensions called out on drawings	POC builds, prototype and preseries builds	2	**42**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
					heating, reduced life							
240	Stator	Stator Core Bonded & Machined	Controls Air Gap	Air gap too small	risk of interference, rubbing, noise, failure	7	Bore diameter too small	3	dimensions called out on drawings	POC builds, prototype and preseries builds, Assembly not possible	2	**42**
241	Stator	Wound Stator Assembly	Carry current of motor into windings (length, size, orientation)	Incorrect definitions for magnet wire leads	cannot connect motor, lead wire insulation failure	7	wire incorrect length	3	Analysis of terminal connections, tooling creation	Poc builds, prototype and preseries builds	2	**42**
242	Stator	Wound Stator Assembly	Connects Incoming Current (Defines /Provides connectivity)	does not define/ provide connectivity	Does not meet customer req'ts, Direction of Rotation problems, Inadequate spacing for heat and assembly, cannot make final connections	7	Incorrect phase identification / wrong position	3	Called out on stator assembly dwg	Poc builds, prototype and preseries builds	2	**42**
243	Inverter	Constraint	The motor shall not exceed the torque rate limit	The motor exceeds the torque rate limit	Unintended acceleration	10	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC shall send a signal if the motor exceeds torque rate limit	4	**40**
244	Rotor	Rotor Core	Transmit Torque	Fails to transmit requested Torque	motor lock	10	excess rpm	2	Controls Code Correct	Resolver Speed Reading/Tacometer reading	2	**40**
245	Motorshaft	Shaft - Rotor Connection	Transmit requested Torque	Fails to Transmit requested Torque	Equipment Shutdown	8	Improper Material Processing Specified	1	assembly method well defined	prototype	5	**40**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
246	Inverter	Constraint	The motor shall not exceed the speed rate limit	The motor exceeds the speed rate limit	Unintended acceleration	10	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC shall verify that the inverter is receiving the speed rate limit	4	**40**
247	Inverter	Constraint	The motor shall operate in torque mode	The motor does not operate in torque mode	Unknown Torque Produced	10	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC receives status signal when speed mode is entered	4	**40**
248	Inverter	Start Up	The inverter shall receive adequate dc voltage from the High Voltage Bus to enable power mode	Inverter does not enable power mode	Inverter not enabled	5	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	In Vehicle Testing - HVSC Status message with Bus Voltage	8	**40**
249	Rotor	Rotor Core	Locate rotor with respect to radial concentricity	rotor is not concentric	Torque ripple, vibration and poor performance	6	Dimensions not correct or not called out	2	called out on drawing	Prototypes	3	**36**
250	Stator	Slot Insulation	Protects wire during winding	Wire damaged during manufacture	Winding short - Motor fails - shock hazard	9	Incorrect thermal, electrical and mechanical properties	2	material spec & supplier data	Poc builds, prototype and preseries builds	2	**36**
251	Stator	Slot Phase Separator	Insulate phases within slot	Fails to insulate	Winding short -	9	Incorrect thermal, electrical and mechanical properties	2	material spec & supplier data	prototype build	2	**36**
252	Stator	Stator Core Bonded & Machined	Conduct flux path to develop EM force	Torque Does Not Meet Specification	Customer Requirement Not Met; reduced motor performance	6	incorrect stack length	3	Analysis, Testing	POC's and prototype builds	2	**36**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
253	Stator	Top Stick	Prevents windings from protruding the ID	Windings protrude ID	Winding short - Motor fails	9	Incorrect dimensions	2	stator lam & component layout	prototype build	2	**36**
254	Stator	Top Stick	Prevents windings from protruding the ID	Windings protrude ID	Winding short - Motor fails	9	Incorrect thermal, electrical and mechanical properties	2	material spec & supplier data	prototype build	2	**36**
255	Stator	Top Wedge	Prevent wires entering stator ID during manufacture	Wire damaged during manufacture	Scrap stator	9	Incorrect thermal, electrical and mechanical properties	2	material spec & supplier data	prototype build	2	**36**
256	Stator	Top Wedge	Insulate wires from lamination teeth	Wire shorts to lamination	Ground fault - shock hazard	9	Incorrect thermal, electrical and mechanical properties	2	material spec & supplier data	prototype build, high pot test, visual	2	**36**
257	Inverter	Communication Output	The inverter shall send the DC power limit	Inverter does not send the DC power limit	Inverter operates outside of safe operation range	9	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC shall verify communication with the inverter	4	**36**
258	Inverter	Communication Output	The inverter shall send the DC power limit	Inverter does not send the DC power limit	Motor operates outside of safe operation range	9	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC shall verify communication with the inverter	4	**36**
259	Motor Assembly	Bearings	Support Motor Weight	Bearings Seize	Repair shaft (expensive)	7	Wrong Type of Lubricant	1	assembly method well defined	prototype	5	**35**
260	Motor Assembly	Bearings	Support Motor Weight	Bearings Seize	Repair shaft (expensive)	7	Insufficient Lubricant	1	assembly method well defined	prototype	5	**35**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
261	Inverter	Inverter I/O - Pin 21	Analog Input	Short To Ground	Inverter Fault - Motor System Disabled - Decrease Performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	1	**35**
262	Inverter	Inverter I/O - Pin 21	Analog Input	Short To Logic	Inverter Fault - Motor System Disabled - Decrease Performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	1	**35**
263	Inverter	Inverter I/O - Pin 21	Analog Input	Open	Inverter Fault - Motor System Disabled - Decrease Performance	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	1	**35**
264	Inverter	Inverter I/O - Pin 37	High side out	Short To Ground	Motor System Disabled - performance decreased	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**35**
265	Inverter	Inverter I/O - Pin 37	High side out	Open	Motor System Disabled - performance decreased	7	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**35**
266	Motor Assembly	Bearings	Support Motor Weight	Bearings Seize	Equipment Shutdown	8	Wrong Type of Lubricant	1	assembly method well defined	prototype	4	**32**
267	Motor Assembly	Bearings	Support Motor Weight	Bearings Seize	Equipment Shutdown	8	Insufficient Lubricant	1	assembly method well defined	prototype	4	**32**
268	Motorshaft	Shaft - Rotor Connection	Transmit requested Torque	Fails to Transmit requested Torque	Rotor Key Shear	8	Improperly specified manufacture	1	assembly method well defined	prototype	4	**32**
269	Motorshaft	Shaft - Rotor Connection	Transmit requested Torque	Fails to Transmit requested Torque	Decrease motor performance	8	Insufficient adhesive	1	assembly method well defined	prototype	4	**32**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
270	Rotor	Rotor Core	Transmit Torque	Fails to transmit requested Torque	delaminate	8	excess rpm	2	Controls Code Correct	Resolver Speed Reading/Tacometer reading	2	**32**
271	Rotor	Rotor Core	Transmit Torque	Fails to transmit requested Torque	delaminate	8	excess torque	2	Controls Code Correct	Measure current demand from Inverter	2	**32**
272	Rotor	Rotor Laminations	Supports Bars	Does not support bars	Lamination rips apart - rotor stops turning/ locks up	8	Insufficient lam strength (material, geometry)	2	Analysis/prior experience	prototype/ Analysis	2	**32**
273	Stator	Stator Core Bonded & Machined	Provide sufficient material for OD Cleanup	OD does not clean up	Poor fit to stator housing, arm slips in in housing, motor fails	8	Incorrect od specified	2	shrink fit analysis and based off previous designs	POC builds, prototype and preseries builds, Assembly not possible	2	**32**
274	Motor Assembly	Bearings	Support Motor Weight	Bearing Slip	Wear and Rub - Motor Performance Decrease	4	misalignment	2	assembly method well defined	Ball Knocking, grinding, visual inspection	4	**32**
275	Inverter	Communication Output	The inverter shall send the motor measurements message	Inverter does not send the motor measurements message	Unknown status of motor	5	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC shall verify communication with the inverter	6	**30**
276	Inverter	Start Up	The inverter shall be verified by the HVSC that it is not transmitting faults. If the inverter is transmitting faults they must be identified, resolved, and	Faults are not cleared	Motor System unable to be used by user	5	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC Shall verify that the inverter is not sending faults	6	**30**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
			cleared before proceeding									
277	Inverter	Communication Output	The inverter shall send the application status message	Inverter does not send application status message	Unknown status of Motor System	5	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC shall verify communication with the inverter	6	**30**
278	Inverter	Communication Output	The inverter shall send the application Status word (Sw) information	Inverter does not send application Sw information	Unknown status of Motor System	5	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC shall verify communication with the inverter	6	**30**
279	Stator	Wound Stator Assembly	Creates Direction of Rotation	Incorrect Rotation	Potential reverse DOR, dissatisfied customer,	5	Hook up diagram incorrect (mixed phase connections)	3	Analysis	POC's and prototype builds	2	**30**
280	Inverter	Communication Output	The inverter shall send the application setup parameters	Inverter does not send the application setup parameters	Motor System unable to be used	5	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC shall verify communication with the inverter	6	**30**
281	Inverter	Communication Output	The inverter shall send DC bus message	Inverter does not send DC bus voltage	Motor System unable to be used	5	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC shall verify communication with the inverter	6	**30**
282	Inverter	Communication Output	The inverter shall send a diagnostic message any time a fault is triggered	Inverter does not send diagnostic message	Unknown status of inverter	5	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC shall verify communication with the inverter	6	**30**
283	Inverter	Communication Output	The inverter shall send a diagnostic	Inverter does not send diagnostic message	Unknown status of motor	5	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test	HVSC shall verify communication with the inverter	6	**30**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
			message any time a fault is triggered						Inverter prior to HEVT Testing			
284	Inverter	Start Up	The inverter shall be verified by the HVSC that it is not transmitting faults. If the inverter is transmitting faults they must be identified, resolved, and cleared before proceeding	Faults are not cleared	Motor System unable to be used by user	5	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC Shall verify that the inverter is not sending faults	6	**30**
285	Inverter	Emergency Response	The inverter shall be disabled through a HVSC CAN command message	The inverter is not disabled by the HVSC	Unintended Motor System Operation	1	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HIL Testing	6	**30**
286	Inverter	Emergency Response	The inverter power relay providing 12V power shall be disabled by a HVSC CAN message	The inverter power relay is not disabled by the HVSC	Unintended Motor System Operation	1	Faulty wiring between power relay and HVSC	5	Inspection from additional CSMS Member	CAN Message will be sent	6	**30**
287	Motor Assembly	Bearings	Support Motor Weight	Bearings Seize	Overload and overheat motor	7	Wrong Type of Lubricant	1	assembly method well defined	prototype	4	**28**
288	Motor Assembly	Bearings	Support Motor Weight	Bearings Seize	Overload and overheat motor	7	Insufficient Lubricant	1	assembly method well defined	prototype	4	**28**
289	Rotor	Rotor Core	Carry Current	resistance too high	excessive heating and	7	wrong material specified	2	Design review, SPEED, FEA analysis	Prototype build	2	**28**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
					loss of performance							
290	Rotor	Rotor Core	Carry Current	resistance too high	excessive heating and loss of performance	7	wrong ending area	2	Design review, SPEED, FEA analysis	Prototype build	2	**28**
291	Rotor	Rotor Core	Transmit Torque	Fails to transmit requested Torque	fatigue, early maintenance costs	7	excess rpm	2	Controls Code Correct	Resolver Speed Reading/Tacometer reading	2	**28**
292	Rotor	Rotor Core	Transmit Torque	Fails to transmit requested Torque	Eccentric rotor - decrease performance	7	Improperly specified design	2	assembly method well defined	prototype/analysis	2	**28**
293	Rotor	Rotor Core	Transmit Torque	Fails to transmit requested Torque	Eccentric rotor - decrease performance	7	Thermal Stress - improperly rated rotor material	2	assembly method well defined	prototype/analysis	2	**28**
294	Rotor	Rotor Core	Transmit Torque	Fails to transmit requested Torque	Eccentric rotor - decrease performance	7	Soft foot or poor base	2	assembly method well defined	prototype/analysis	2	**28**
295	Rotor	Rotor Core	Transmit Torque	Fails to transmit requested Torque	Broken Rotor Bars - decrease performance	7	improperly specified center	2	assembly method well defined	prototype/analysis	2	**28**
296	Rotor	Rotor Core	Transmit Torque	Fails to transmit requested Torque	Broken Rotor Bars - decrease performance	7	Soft foot or poor base	2	assembly method well defined	prototype/analysis	2	**28**
297	Motor Mount	Floorplan to Motor Connection	Handle Reaction Torque/ Locate Motor	Fails to handle reaction torque	Mounting Structure Yield/Fracture	2	Insufficient weld strength	7	FEA	FEA	2	**28**
298	Inverter	Communication Output	The inverter shall send the motor and inverter temperature	Inverter does not send the motor temperature	Motor overheats	7	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC shall verify communication with the inverter	4	**28**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
299	Inverter	Communication Output	The inverter shall send the motor and inverter temperature	Inverter does not send inverter temperature	Inverter overheats	7	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC shall verify communication with the inverter	4	**28**
300	Inverter	Communication Output	The inverter shall send the power stage temperature	Inverter does not send the power stage temperature	Inverter overheats	7	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC shall verify communication with the inverter	4	**28**
301	Inverter	Communication Output	The inverter shall send the PCB temperature	Inverter does not send the PCB temperature	Inverter overheats	7	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC shall verify communication with the inverter	4	**28**
302	Inverter	Constraint	The motor shall decay from peak torque to continuous torque based on thermal considerations	The motor does not decay from peak to continuous torque based on temperature	Motor overheats	7	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC shall test for temperature in SIL	4	**28**
303	Inverter	Constraint	The inverter shall not exceed the maximum rated temperature	Inverter exceeds maximum rated temperature	Inverter overheats	7	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC shall continuously monitor inverter temperature	4	**28**
304	Inverter	Inverter I/O - Pin 39	Logic Supply	Short To Logic	Normal Operation	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	5	**25**
305	Motor Wires	3-Phase Lines	Transmit AC	Fails to Transmit required current	Overheating	3	Prolonged Current Demand	4	Controls Code Correct	CAN Signal	2	**24**
306	Rotor	Rotor Laminations	Fit with neighboring laminations	Does not fit well with other laminations	Gaps in lam stack - low efficiency	4	Burr alignment not correctly identified	2	Called on drawing, previous experience	POC's and prototypes	3	**24**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
307	Rotor	Rotor Laminations	Fit with neighboring laminations	Does not fit well with other laminations	Gaps in lam stack - low efficiency	4	Thickness tolerance not clearly defined	2	Called on drawing, previous experience	POC's and prototypes	3	**24**
308	Stator	Wound Stator Assembly	Produce correct armature flux pattern (windings)	Does not define winding pattern (KWD)	incorrect rotation, degredated performance	6	Incorrect KWD	2	analysis, similar designs	Poc builds, prototype and preseries builds	2	**24**
309	Inverter	Emergency Response	The inverter shall be disabled through a HVSC CAN command message	The inverter is not disabled by the HVSC	Unintended Motor System Operation	1	Improper code in the HVSC	4	SIL and HIL testing	HIL Testing	6	**24**
310	Inverter	Emergency Response	The inverter power relay providing 12V power shall be disabled by a HVSC CAN message	The inverter power relay is not disabled by the HVSC	Unintended Motor System Operation	1	Improper code in the HVSC	4	SIL and HIL testing	CAN Message will be sent	6	**24**
311	Motor Mount	Floorplan to Motor Connection	Handle Reaction Torque/ Locate Motor	Fails to handle reaction torque	Mounting Structure Yield/Fracture	10	Supporting Structure failing	1	FEA	FEA	2	**20**
312	Motorshaft	Shaft - Rotor Connection	Transmit requested Torque	Fails to Transmit requested Torque	Rotor Key deformation	5	improper adhesive	1	assembly method well defined	prototype	4	**20**
313	Rotor	Rotor Core	Provide material for final machining operation	does not clean up or removal of tooth tips	loss of torque at high speed	5	Dimensioned incorrectly	2	FEA analysis on lam stack OD vs housing ID	Prototype build	2	**20**
314	Inverter	Constraint	The inverter shall operate above a	Inverter does not operate above the minimum voltage	Inverter does not operate as expected	5	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test	HVSC shall continuously monitor the voltage	4	**20**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
			minimum voltage						Inverter prior to HEVT Testing	going into the inverter		
315	Inverter	Constraint	The motor shall not exceed the maximum rated torque	Motor exceeds maximum rated torque	Too much torque produced by motor to meet driver demand	1	Faulty wiring between Inverter and HVSC	5	Inspection from additional CSMS Member	HVSC shall verify communication with the inverter	4	**20**
316	Motor Assembly	Bearings	Support Motor Weight	Bearing Slip	Overheating	4	poor lubrication	1	assembly method well defined	prototype	4	**16**
317	Motor Wires	3-Phase Lines	Transmit AC	Fails to Transmit required current	not desired regenerative braking	4	Maintain recommend bend radius	2	Assembly method well defined	Virtual Analysis/CAD Routing	2	**16**
318	Stator	Wound Stator Assembly	Defines clean mounting surface	do not have clean mounting surface	cannot assemble armature into housing	4	surface that cannot have VPI not defined	2	defined on drawing	Poc builds, prototype and preseries builds	2	**16**
319	Inverter	Constraint	The inverter shall remain above a minimum temperature	Inverter falls below the minimum temperature	Inverter operates outside of safe operation range	4	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC shall continuously monitor the temperature of the inverter	4	**16**
320	Inverter	Constraint	The inverter shall operate below a maximum voltage	Inverter exceeds the maximum voltage	Inverter operates outside of safe operation range	1	Improper code in the HVSC	4	SIL and HIL testing	HVSC shall send a signal to the driver if the inverter is not enabled	4	**16**
321	Inverter	Constraint	The motor shall operate below a maximum current	Inverter exceeds the maximum current	Inverter operates outside of safe operation range	1	Improper code in the HVSC	4	SIL and HIL testing	HVSC shall send a signal to the driver if the inverter is not enabled	4	**16**
322	Inverter	Emergency Response	The inverter shall be disabled through a HVSC CAN	The inverter is not disabled by the HVSC	Unintended Motor System Operation	1	Overloaded electric torque bus	2	Place electric torque on separate bus	HVSC shall monitor bus loading to determine if signals are being lost	8	**16**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
			command message									
323	Rotor	Rotor Core	Transmit Torque	Fails to transmit requested Torque	Broken Rotor Bars - decrease performance	7	Thermal Stress	2	assembly method well defined	Thermistor	1	**14**
324	Stator	Stator Windings	Transmit Torque	Fails to transmit requested Torque	Open or Shorted Stator winding	7	Improper Isolation	1	assembly method well defined	prototype/analysis	2	**14**
325	Motor Mount	Floorplan to Motor Connection	Handle Reaction Torque/ Locate Motor	Fails to handle reaction torque	Bolt Shear	2	Bolt Torque Improperly Specified	1	Specified Torque Specs/ marks	Torque Wrench/Quality	7	**14**
326	Stator	Stator Core Bonded & Machined	Controls Air Gap	Excessive Eccentricity	risk of interference, rubbing, noise, failure, bearing loads	2	Incorrect perp. On frame end lamination	3	Perp does not have an effect on air gap tolerance.	POC builds, prototype and preseries builds, Assembly not possible	2	**12**
327	Stator	Stator Lamination	Allows for machined OD	Not enough material for clean up	Entire OD not clean up	3	Incorrect OD Specification	2	Based off existing designs	POC's and Prototypes	2	**12**
328	Inverter	Emergency Response	The inverter power relay providing 12V power shall be disabled by a HVSC CAN message	The inverter power relay is not disabled by the HVSC	Unintended Motor System Operation	1	Overloaded Mid-Speed LAN Bus	2	Place mid speed on separate bus	CAN Message will be sent	6	**12**
329	Rotor	Rotor Core	Transmit Torque	Fails to transmit requested Torque	motor lock	10	overheating	1	Controls Code Correct	Thermistor	1	**10**
330	Inverter	Constraint	The inverter shall log the input and output messages	Inverter does not log input messages	Unknown prior status of motor system	1	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	None - InMotion defined and programmed function	10	**10**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
331	Inverter	Constraint	The inverter shall log the input and output messages	Inverter does not log output messages	Unknown prior status of motor system	1	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	None - InMotion defined and programmed function	10	**10**
332	Rotor	Rotor Core	Transmit Torque	Fails to transmit requested Torque	delaminate	8	overheating	1	Controls Code Correct	Thermistor	1	**8**
333	Stator	Slot Phase Separator	Define straightness of slot	Slot not straight	Loss of performance	2	miss spec of skew	2	called out on drawing	POC builds, prototype and preseries builds, Assembly not possible	2	**8**
334	Inverter	Constraint	The motor shall not exceed the maximum rated speed	Motor exceeds maximum rated speed	Too much torque produced by motor to meet driver demand	1	Improper code in the Inverter	2	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	The inverter sends signal to HVSC	4	**8**
335	Inverter	Inverter I/O - Pin 02	Motor Temperature Sensor 1 GND	Short To Ground	Normal Operation	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**
336	Inverter	Inverter I/O - Pin 04	Motor Temperature Sensor 2 GND	Short To Ground	Normal Operation	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**
337	Inverter	Inverter I/O - Pin 05	Resolver Chassis (Shield)	Short To Ground	Normal Operation	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**
338	Inverter	Inverter I/O - Pin 22	J1939 H in	Short To Ground	No Effect - Not Used	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
339	Inverter	Inverter I/O - Pin 22	J1939 H in	Short To Logic	No Effect - Not Used	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**
340	Inverter	Inverter I/O - Pin 22	J1939 H in	Open	Normal Operation	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**
341	Inverter	Inverter I/O - Pin 23	J1939 H out	Short To Ground	No Effect - Not Used	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**
342	Inverter	Inverter I/O - Pin 23	J1939 H out	Short To Logic	No Effect - Not Used	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**
343	Inverter	Inverter I/O - Pin 23	J1939 H out	Open	Normal Operation	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**
344	Inverter	Inverter I/O - Pin 24	J1939 H back up	Short To Ground	No Effect - Not Used	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**
345	Inverter	Inverter I/O - Pin 24	J1939 H back up	Short To Logic	No Effect - Not Used	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**
346	Inverter	Inverter I/O - Pin 24	J1939 H back up	Open	Normal Operation	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**
347	Inverter	Inverter I/O - Pin 25	J1939 L in	Short To Ground	No Effect - Not Used	1	Improper wire harness assembly	5	Component Specification	Normal Operation	1	**5**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
									Documents and Proper Training			
348	Inverter	Inverter I/O - Pin 25	J1939 L in	Short To Logic	No Effect - Not Used	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**
349	Inverter	Inverter I/O - Pin 25	J1939 L in	Open	Normal Operation	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**
350	Inverter	Inverter I/O - Pin 26	J1939 L out	Short To Ground	No Effect - Not Used	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**
351	Inverter	Inverter I/O - Pin 26	J1939 L out	Short To Logic	No Effect - Not Used	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**
352	Inverter	Inverter I/O - Pin 26	J1939 L out	Open	Normal Operation	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**
353	Inverter	Inverter I/O - Pin 27	J1939 L back up	Short To Ground	No Effect - Not Used	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**
354	Inverter	Inverter I/O - Pin 27	J1939 L back up	Short To Logic	No Effect - Not Used	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**
355	Inverter	Inverter I/O - Pin 27	J1939 L back up	Open	Normal Operation	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
356	Inverter	Inverter I/O - Pin 28	Digital Input 1	Short To Ground	Incorrect Signal - Decrease motor system performance	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training		1	**5**
357	Inverter	Inverter I/O - Pin 28	Digital Input 1	Short To Logic	Incorrect Signal - Decrease motor system performance	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training		1	**5**
358	Inverter	Inverter I/O - Pin 28	Digital Input 1	Open	Inverter Fault - Motor System Disabled - Decrease Performance	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	1	**5**
359	Inverter	Inverter I/O - Pin 31	Digital Input GND	Short To Ground	Normal Operation	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**
360	Inverter	Inverter I/O - Pin 31	Digital Input GND	Short To Logic	Incorrect Signal - Decrease motor system performance	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects difference between commanded and measured	1	**5**
361	Inverter	Inverter I/O - Pin 31	Digital Input GND	Open	Inverter Fault - Motor System Disabled - Decrease Performance	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	HVSC detects Inverter Fault	1	**5**
362	Inverter	Inverter I/O - Pin 32	~Safe Torque Off (High)	Short To Logic	Normal Operation	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**
363	Inverter	Inverter I/O - Pin 33	Safe Torque Off (Low)	Short To Ground	Normal Operation	1	Improper wire harness assembly	5	Component Specification	Normal Operation	1	**5**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
									Documents and Proper Training			
364	Inverter	Inverter I/O - Pin 34	High side out GND	Short To Ground	Normal Operation	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**
365	Inverter	Inverter I/O - Pin 34	High side out GND	Open	Normal Operation	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**
366	Inverter	Inverter I/O - Pin 36	Logic Supply	Short To Logic	Normal Operation	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**
367	Inverter	Inverter I/O - Pin 37	High side out	Short To Logic	Normal Operation	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**
368	Inverter	Inverter I/O - Pin 38	Logic Supply - GND	Short To Ground	Normal Operation	1	Improper wire harness assembly	5	Component Specification Documents and Proper Training	Normal Operation	1	**5**
369	Motor Mount	Floorplan to Motor Connection	Handle Reaction Torque/ Locate Motor	Fails to handle reaction torque	Bolt Shear	2	Improperly specified Bolt	1	FEA/ strain gauging	Analysis	2	**4**
370	Motor Mount	Floorplan to Motor Connection	Handle Reaction Torque/ Locate Motor	Fails to handle reaction torque	Bolt Shear	2	shock loads	1	No prevention method	FEA	2	**4**
371	Inverter	Constraint	The motor shall not exceed the maximum rated speed	Motor exceeds maximum rated speed	Too much torque produced by motor to meet driver demand	1	Faulty wiring between Inverter and HVSC	1	Inspection from additional CSMS Member	HVSC shall verify communication with the inverter	4	**4**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
372	Inverter	Constraint	The motor shall not exceed the maximum rated torque	Motor exceeds maximum rated torque	Too much torque produced by motor to meet driver demand	1	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	The inverter sends signal to HVSC	4	**4**
373	Inverter	Constraint	The inverter shall operate below a maximum voltage	Inverter exceeds the maximum voltage	Inverter operates outside of safe operation range	1	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC shall continuously monitor the voltage going into the inverter	4	**4**
374	Inverter	Constraint	The motor shall operate below a maximum current	Inverter exceeds the maximum current	Inverter operates outside of safe operation range	1	Improper code in the Inverter	1	None - Supplier Inspection. Have Supplier bench test Inverter prior to HEVT Testing	HVSC shall continuously monitor the current going into the inverter	4	**4**
375	Motor Mount	Floorplan to Motor Connection	Handle Reaction Torque/ Locate Motor	Fails to handle reaction torque	Mounting Structure Yield/Fracture	1	Overloading (Mass)	1	Specified Mass Limits	FEA	2	**2**
376	Inverter	Inverter I/O - Pin 12	Digital Input GND	Short To Ground	Normal Operation	1	Improper wire harness assembly	1	Component Specification Documents and Proper Training	HVSC cannot detect fault	1	**1**
377	Inverter	Inverter I/O - Pin 12	Digital Input GND	Short To Logic	Incorrect Signal - Decrease motor system performance	1	Improper wire harness assembly	1	Component Specification Documents and Proper Training	HVSC cannot detect fault	1	**1**
378	Inverter	Inverter I/O - Pin 12	Digital Input GND	Open	Inverter Fault - Motor System Disabled - Decrease Performance	1	Improper wire harness assembly	1	Component Specification Documents and Proper Training	HVSC cannot detect fault	1	**1**
379	Inverter	Inverter I/O - Pin 13	Digital Input 4	Short To Ground	Incorrect Signal - Decrease	1	Improper wire harness assembly	1	Component Specification	HVSC cannot detect fault	1	**1**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
					motor system performance				Documents and Proper Training			
380	Inverter	Inverter I/O - Pin 13	Digital Input 4	Short To Logic	Incorrect Signal - Decrease motor system performance	1	Improper wire harness assembly	1	Component Specification Documents and Proper Training	HVSC cannot detect fault	1	**1**
381	Inverter	Inverter I/O - Pin 13	Digital Input 4	Open	Inverter Fault - Motor System Disabled - Decrease Performance	1	Improper wire harness assembly	1	Component Specification Documents and Proper Training	HVSC cannot detect fault	1	**1**
382	Inverter	Inverter I/O - Pin 14	Digital Input 3	Short To Ground	Incorrect Signal - Decrease motor system performance	1	Improper wire harness assembly	1	Component Specification Documents and Proper Training	HVSC cannot detect fault	1	**1**
383	Inverter	Inverter I/O - Pin 14	Digital Input 3	Short To Logic	Incorrect Signal - Decrease motor system performance	1	Improper wire harness assembly	1	Component Specification Documents and Proper Training	HVSC cannot detect fault	1	**1**
384	Inverter	Inverter I/O - Pin 14	Digital Input 3	Open	Inverter Fault - Motor System Disabled - Decrease Performance	1	Improper wire harness assembly	1	Component Specification Documents and Proper Training	HVSC cannot detect fault	1	**1**
385	Inverter	Inverter I/O - Pin 15	Digital Input 2	Short To Ground	Incorrect Signal - Decrease motor system performance	1	Improper wire harness assembly	1	Component Specification Documents and Proper Training	HVSC cannot detect fault	1	**1**
386	Inverter	Inverter I/O - Pin 15	Digital Input 2	Short To Logic	Incorrect Signal - Decrease motor system performance	1	Improper wire harness assembly	1	Component Specification Documents and Proper Training	HVSC cannot detect fault	1	**1**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
387	Inverter	Inverter I/O - Pin 15	Digital Input 2	Open	Inverter Fault - Motor System Disabled - Decrease Performance	1	Improper wire harness assembly	1	Component Specification Documents and Proper Training	HVSC cannot detect fault	1	**1**
388	Inverter	Inverter I/O - Pin 16	Digital Input GND	Short To Ground	Normal Operation	1	Improper wire harness assembly	1	Component Specification Documents and Proper Training	HVSC cannot detect fault	1	**1**
389	Inverter	Inverter I/O - Pin 16	Digital Input GND	Short To Logic	Incorrect Signal - Decrease motor system performance	1	Improper wire harness assembly	1	Component Specification Documents and Proper Training	HVSC cannot detect fault	1	**1**
390	Inverter	Inverter I/O - Pin 16	Digital Input GND	Open	Inverter Fault - Motor System Disabled - Decrease Performance	1	Improper wire harness assembly	1	Component Specification Documents and Proper Training	HVSC cannot detect fault	1	**1**
391	Inverter	Inverter I/O - Pin 17	Digital Input GND	Short To Ground	Normal Operation	1	Improper wire harness assembly	1	Component Specification Documents and Proper Training	HVSC cannot detect fault	1	**1**
392	Inverter	Inverter I/O - Pin 17	Digital Input GND	Short To Logic	Incorrect Signal - Decrease motor system performance	1	Improper wire harness assembly	1	Component Specification Documents and Proper Training	HVSC cannot detect fault	1	**1**
393	Inverter	Inverter I/O - Pin 17	Digital Input GND	Open	Inverter Fault - Motor System Disabled - Decrease Performance	1	Improper wire harness assembly	1	Component Specification Documents and Proper Training	HVSC cannot detect fault	1	**1**
394	Inverter	Inverter I/O - Pin 18	Analog Input	Short To Ground	Inverter Fault - Motor System Disabled -	1	Improper wire harness assembly	1	Component Specification	HVSC cannot detect fault	1	**1**

Line No.	Subsystem	Part/Interface	Design Function	Potential Failure Mode	Failure Effect	S	Potential Cause	O	Current Design Controls - Prevention Method	Current Design Controls - Detection Method	D	RPN
					Decrease Performance				Documents and Proper Training			
395	Inverter	Inverter I/O - Pin 18	Analog Input	Short To Logic	Inverter Fault - Motor System Disabled - Decrease Performance	1	Improper wire harness assembly	1	Component Specification Documents and Proper Training	HVSC cannot detect fault	1	**1**
396	Inverter	Inverter I/O - Pin 18	Analog Input	Open	Inverter Fault - Motor System Disabled - Decrease Performance	1	Improper wire harness assembly	1	Component Specification Documents and Proper Training	HVSC cannot detect fault	1	**1**